Multi-Microgrid Impact Assessment Using Multi Criteria Decision Aid Methods

Julija Vasiljevska, Joao A. Peças Lopes, *Senior Member, IEEE*, and Manuel A. Matos, *Member, IEEE*

***Abstract* — Recognizing the benefit that one can get by exploiting the Micro-Grid (MG) concept, as an active part of the Low Voltage (LV) network comprising several micro-generation (µG) sources, controllable loads and storage devices, is a key issue towards the MG concept deployment. Furthermore, the MG concept is extended into Multi-Micro Grid (MMG) concept, identifying the benefits that can be obtained at Medium Voltage (MV) level.**

The main idea behind this research is to show what one gains and what one looses by setting up the MG concept. Therefore, the benefits reported, are evaluated through a cost-benefit approach by modeling the problem as a multi-attribute problem using several Decision-Aid (DA) techniques to capture different Decision Maker (DM) preference structures.

***Index Terms*-- micro-generation (µG), Micro-Grid (MG), Multi Micro-Grid (MMG), active network management, multi-attribute assessment, Decision-Aid (DA).**

I. INTRODUCTION

MICROGENERATION (µG) technologies have progressed from isolated operation, when used in remote areas, to a grid interconnected mode that may involve its active management under the concept of a Microgrid (MG). A MG can be defined as an active cell within the Low Voltage (LV) network, according to the European concept of MG, which consists of several µG sources, storage devices and controllable loads, having total installed capacity of few kW up to a few hundreds of kW. MG mostly operates interconnected to the main distribution grid, but also islanded, in case of external faults. The management and control of a MG involves a hierarchical control system architecture comprises the following three control levels [1]-[2]:

1. local Microsource Controllers (MC) and Load Controllers (LC);
2. Microgrid System Central Controller (MGCC);
3. Central Autonomous Management Controller (CAMC).

Each MC follows requests from the central controller, when connected to the power grid, and perform local optimization of the µG active and reactive power production, and fast load tracking following an islanding situation. LCs installed at the controllable loads provide load control capabilities following orders from the MGCC for load management.

The MGCC is responsible for optimization of the MG operation. It uses the market prices of electricity and gas and grid security concerns to determine the amount of power that the MG should draw from the distribution system, thus optimizing the local production capabilities.

Regulators are one of the players that need to address the benefits µG can bring to distribution networks in order to find out the right incentives to encourage Distribution System Operators (DNO) and µG owners to be involved in the deployment of the MG concept. Furthermore, potential conclusions can be drawn regarding the share of costs and benefits among the entities involved in the deployment of the MG concept. The development of MG solutions requires the adoption of individual MG optimization procedures [1], being possible to evaluate the overall benefits one can get from a MG, namely when operated in real market environment. For this purpose, an active local management is adopted at each MG level, in terms of µG optimization and load management performed through Demand Side Bidding (DSB). Section II describes the local optimization procedure at the MG level. Section III extends the MG concept to a Multi Micro-Grid (MMG) system where several MGs are connected in a MV grid, thereby identifying the global technical and economic benefits that can be obtained at a MV network level. In sections IV and V different multi-criteria evaluation techniques have been applied in order to capture different complexity levels of the DM preference structure.

II. MICROGRID OPTIMIZATION METHODOLOGY

In this research several µG technologies have been considered to be present within a MG, such as Micro-Turbine (MT), micro Wind Turbine (WT) and Photovoltaics (PVs).

In order to evaluate the benefits that can be obtained from the presence of MG, different study case scenarios are

---

This work was supported by the E.U research project “More Microgrids” (Contract No SES6 -019864)

J.Vasiljevska is with the Faculty of Engineering at the University of Porto (FEUP), and Instituto de Engenharia de Sistemas e Computadores do Porto (INESC Porto).(e-mail: julija.vasiljevska@fe.up.pt).

Joao. A. Peças Lopes is with the Faculty of Engineering at the University of Porto (FEUP), and Instituto de Engenharia de Sistemas e Computadores do Porto (INESC Porto (e-mail: jpl@fe.up.pt)

Manuel A. Matos is with the Faculty of Engineering at the University of Porto (FEUP), and Instituto de Engenharia de Sistemas e Computadores do Porto (INESC Porto (e-mail: mam@fe.up.pt)

considered regarding different levels of μG installed capacity within the MGs and different electricity market prices. What is expected to take place is an increase of μG production in periods of high electricity market prices.

The MG optimization procedure – active network management - is performed at a Micro Grid Central Controller (MGCC) [2], housed in the local MV/LV substation, requiring the execution of the following steps:

1. Each unit within the MG bids for production for the next hour in n-minutes intervals, according to the electricity market prices, operating costs of the unit and the profit for the unit's owner;
2. Each consumer within the MG bids for their load supply for the next hour in the same n-minutes intervals, where each bid reflects the amount of energy he is willing to pay at that time interval taking into account the possibility of shifting to the next time interval, where the electricity price is lower, a certain percentage of its load (considered as "low priority" load);
3. Solving the optimization procedure by defining the MG units being committed and the consumers' bids being accepted.

The rest of the demand is served from the upstream network at real market prices [6].

In this optimization procedure the Renewable Energy Sources (RES) within the MG are not considered as competitive units, i.e. they are always dispatched once their primary energy resource is available. Therefore the only units that bid within the MG are the fuel-consuming units, defined as controllable units, since their production is in correlation with the electricity market prices.

Moreover, we are assuming that all consumers within the MG are price-sensitive, i.e. they may respond to the high prices at the load peak period, by shifting 10% of their demand to the next time interval of lower electricity price.

Since the main idea of this work is the impact assessment that several MGs may have at upper network level (MV level), several scenarios are created regarding the MG installed capacity at the LV grid, ranging from 10% to 30% of the peak power of the corresponding MV/LV substation. Since two independent analyses, regarding the type of the distribution network, rural and urban, take place, the percentage of μG technology regarding the total MG installed capacity is different for these two types of networks. In the case of a rural network most of the MGs include mainly RES (with 80% of PV and 20% of WT, from the total percentage of RES being installed), gradually increasing its installed capacity from 10% to 30%. Since the installation of MTs is not feasible in rural areas, once natural gas networks are not easily available, only 4 MGs comprise MTs, with installed capacity of 30kW each, with efficiency of 26% for burning a natural gas [11]. The fuel price is assumed to be 10 €ct/m^3 [8]. Regarding the RES units, its generation depends on the availability of the primary energy resources (wind and sun). Typical wind speed and daily sun radiation data for Portugal have been used to define the generation levels for these sources [10]. For the micro WT, an average capacity factor of 40% was assumed.

The daily load consumption profiles, seen from the MG LV/MV transformer, with and without the MG active management are presented in the following figures for the case of maximum MG installed capacity, i.e. 30% of the peak power.

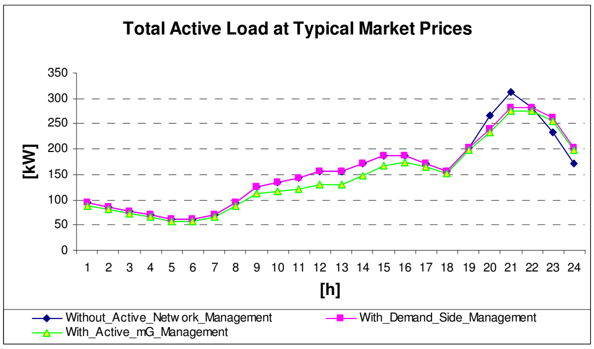

Fig 1.Active Network Management in period of typical electricity market prices

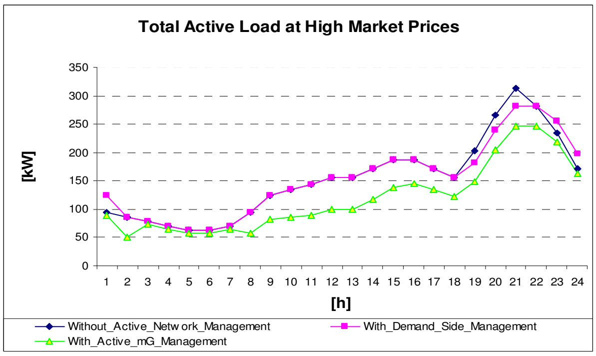

Fig 2.Active Network Management in period of high electricity market prices

Fig. 1 presents the outcome of the local active network management for a given load scenario in periods of typical electricity market prices, whereas Fig. 2 introduces additional value of the active network management in periods of high electricity market prices when adopting the local optimum management procedure described before. The area bellow the bottom curve indicates the amount of energy needed to be bought from the upstream network at open market prices. As expected, high electricity prices yields higher MG production, i.e. dispatch of the fuel-consuming units (MT in our case) and lower amount of energy to be bought from the upstream network.

III. QUANTIFICATION OF THE TECHNICAL, ECONOMIC AND ENVIRONMENTAL IMPACT OF A MULTI-MICROGRID

After having locally optimized the operation of a single MG, the next step is moving towards higher network level. Namely, the idea was setting up several MGs and identifying the impact at MV level. Since the whole application is taking place in a real market environment, reflecting realistic market prices, several scenarios are created in respect to four evaluation alternatives, namely, without MMG (alternative A), with MMG and 10% μG installed capacity within the MG (alternative B), with MMG and 20% μG installed capacity within the MG (alternative C) and with MMG and 30% μG installed capacity within the MG (alternative D).

Our calculations are based on data from real MV distribution networks. Two types of distribution networks have been used: rural and urban distribution networks, in regard to which two independent analyses are conducted. The idea of the independent consideration of the two networks comes from the fact that we are facing different technical issues in each of the networks. Typical rural networks would yield voltage drop problems due to the length of the wires, whereas in typical urban networks the critical issue regards to congestion problems in some branches.

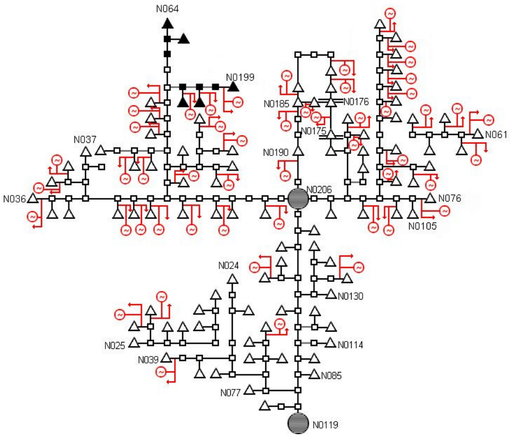

Figure 3. Medium-voltage rural network

Fig. 3 shows a typical rural network, which was used in our study, with several MGs (described in the figure by a generator and a load). The ten worst nodes regarding the voltage drop are designated in black.

Fig. 4 presents the minimum voltage levels reached in the network after a load increase in every node during x years, assuming an annual load rate increase of 3%. The results presented in Fig.4 consider the case of 30% μG installed capacity within the MG of the local peak load, for a typical day of high electricity market prices, when the MG units' production reaches it's the higher value. The investment deferral time is defined by the period of time between two moments: a) when the minimum voltage level is reached in the most critical bus for a scenario with certain percentage of MG installed capacity within the MMG b) regarding to the one without MMG.

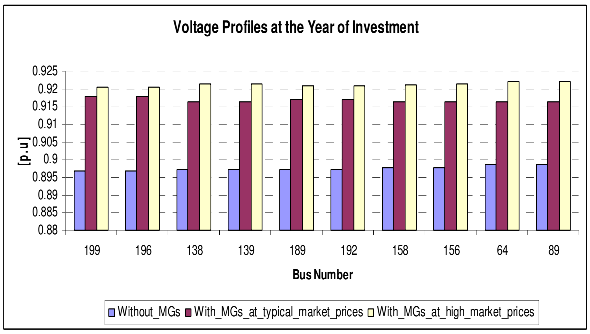

Fig 4. Minimum voltage profiles at ten worst nodes due to voltage drop

Moreover, it is clearly evident that strategically located MGs may systematically reduce the distribution network losses, beneficial to the Distribution Utility (DU), as an entity responsible or mandated to keep losses at low levels. Nevertheless, this "technical" benefit of loss reduction resulting from the MGs presence can be translated into an economic benefit and considered as one of the criteria of the multi-attribute problem described in the next section. Fig. 5 presents the total active losses for a typical day of high electricity market prices for the case of 30% μG installed regarding the MG peak load.

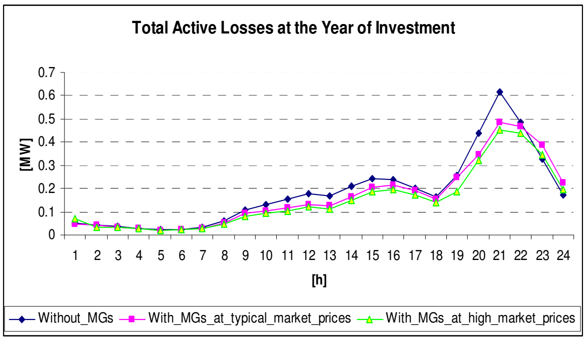

Fig 5. Total active losses in a typical MV rural network for a day of typical and high electricity market prices

What can be observed from the above figure is a significant active power losses reduction at peak hour, regarding the case of not having MGs installed, reaching 19.7% of reduction for a day with typical electricity market prices and 24.6% in a day of high electricity prices, since the controllable generation units within each MG are capable of providing energy in more favourable economic conditions than buying it from the upstream network.

Similar analyses are applied for a typical urban network, whereas in this case the line congestion levels define the criteria through which it is possible to identify the period of time that investment in reinforcements can be deferred.

Fig. 6 presents a typical urban network used in our study.

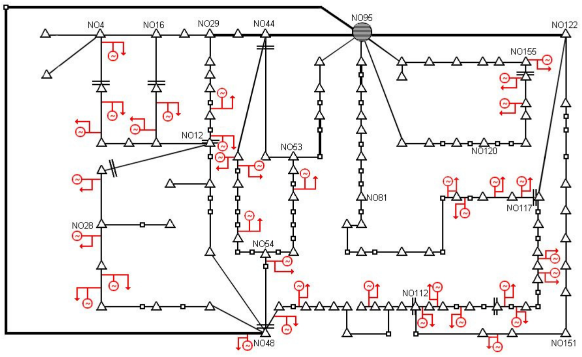

Fig 6. Typical Medium Voltage Urban Network

Similarly, several MGs, with a total installed capacity limited to 20% of the MG peak load were considered for this study case. The mix of μG technologies in each MG, placed as depicted in Fig.6, is 25% RES (mainly PVs, since it is an urban area) and 75% of controllable units, namely MT. The ten most congested lines are shown in bold.

What is evident from Fig.7 is a significant congestion level reduction at the peak hour in the ten most congested lines, especially for period of high electricity prices when the MT units are expected to be fully dispatched. The recorded values reach 7.9% congestion level reduction in the most congested line in respect to the case with no MGs being installed, for typical electricity prices, and reduction of 15.7% in the most congested line for a period of high electricity market prices.

As expectable, a large active losses reduction has been achieved, reaching value of 23.7% at the peak hour, for a period of high electricity prices in respect to the case without MGs being installed. (Fig.8).

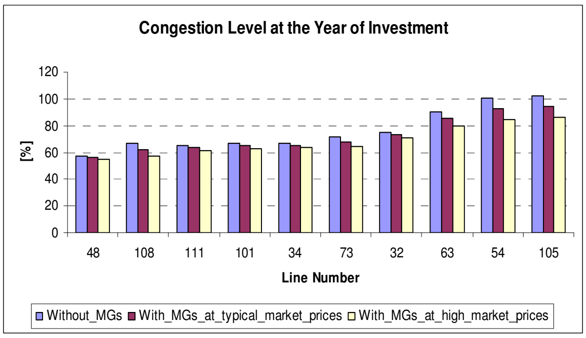

Fig 7. Congestion level at the ten most congested lines at the year of investment

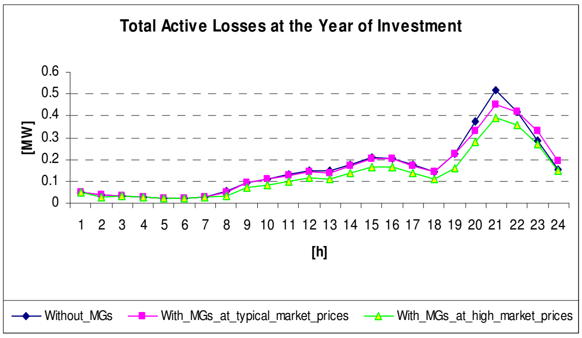

Fig 8. Total active losses in a typical MV urban network for a day of typical and high electricity market prices

All the technical issues, in terms of voltage drop (rural networks), congestion level (urban networks) and total active losses, are addressed through simulation, namely power flow studies, defining the attributes of the multi-attribute problem considered in the next section.

IV. MULTI-ATTRIBUTE ASSESSMENT OF THE MMG IMPACT DEPLOYMENT

Since the problem is modelled as a multi-criteria, more accurately, multi-attribute problem, the attributes are explicitly defined, addressed in the previous section through simulation. Moreover, the criteria of the problem are defined through the attributes, recognizing three main criteria in our case: total annualized cost for putting in place MMG, investment deferral and active losses. Therefore, the installation cost is considered as an a priori cost, annualized, as well as the MMG operation net cost, subject to careful examination with regards to avoiding duplications of cost or benefits. The cost of putting in place the MMG, in terms of MG communication and control infrastructure that is essential for the coordinated control of the μG units in MG operation, is considered as installation cost.

The multi-criteria analysis presented in this section are applied for the case of the rural MV network, having the possibility of application at the urban MV network as well.

Four main alternatives are considered from the DM perspective, namely no-MMG (alternative A), with MMG and 10% μG installed capacity within the each MG (alternative B), with MMG and 20% μG installed capacity within the each MG (alternative C) and with MMG and 30% μG installed capacity within the each MG (alternative D). Having concluded in the first part of the research, that market prices influence the MG production, two scenarios regarding the prices are created, corresponding to days with high and typical electricity market prices [6]. Furthermore, considering the investment deferral, two scenarios regarding the load growth are added. Therefore, four scenarios have been created: typical electricity prices and 3% load growth (scenario 1), typical electricity prices and 4% load growth (scenario 2), high electricity prices and 3% load growth (scenario 3), and high electricity prices and 4% load growth (scenario 4).

The MMG installation cost includes the cost of the MGCC in each of the MGs, the cost of the MC for each type of source considered within each MG, as well as the LC for each of the consumers within each MG being part of the MMG. A relevant assumption is made regarding the share of cost of the MG's local controllers, namely MC and LC within each MG, between the DNO and the consumers, assuming 50% of this cost is covered by the distribution utility and the rest is equally distributed among all the consumers within each MG, due to the fact that both sides exploit benefits from the MG deployment. The cost for putting in place the MGCC is covered by the DNO. Indicative values for the cost of each local controller were used, namely 300€ for each micro wind generator and PVs local controller, 500€ for each MGCC local controller and 100€ for each LV load local controller. The cost of the MGCC is assumed to be 500€. The MMG net operation cost comprises the fuel cost for the fuel-consuming units within each MG, being dispatched at the peak hour.

Table I presents the attributes of the first evaluation criteria considered. The MMG net operation cost has zero value for alternatives B, C and D in the first two scenarios, due to the fact that the MTs, as controllable units, are not dispatched in periods of typical electricity prices, since it is more economically beneficial to buy power from the upstream network.

Table II displays the attributes for the three evaluation criteria: total MMG cost (C_1), investment deferral (C_2) and active losses (C_3) for each of the four scenarios created.

TABLE I
CALCULATED ATTRIBUTES FOR THE FIRST EVALUATION CRITERIA

Alternative	Scenario	Ann.Inv Cost [€]	Operation Cost [€]	Total cost Ann. [€]
A		0	0	0
B	1	96 696.63	0	96 696.63
C		112 893.25	0	112 893.25
D		129 089.88	0	129 089.88
A		0	0	0
B	2	96 696.63	0	96 696.63
C		112 893.25	0	112 893.25
D		129 089.88	0	129 089.88
A		0	0	0
B	3	96 696.63	430.66	97 127.29
C		112 893.25	430.66	113 323.91
D		129 089.88	430.66	129 520.54
A		0	0	0
B	4	96 696.63	430.66	97 127.29
C		112 893.25	430.66	113 323.91
D		129 089.88	430.66	129 520.54

TABLE II
EVALUATION CRITERIA FOR THE MULTI-ATTRIBUTE PROBLEM

		Evaluation Criteria		
Alternative	Scenarios	Total cost Ann. (C_1) [€]	Invest. Deferral (C_2) [years]	Active Losses (C_3) [MW]
A		0	0	0.618
B	1	96 696.63	3	0.496
C		112 893.25	4	0.491
D		129 089.88	4	0.485
A		0	0	0.601
B	2	96 696.63	3	0.483
C		112 893.25	3	0.477
D		129 089.88	3	0.471
A		0	0	0.618
B	3	97 127.29	4	0.466
C		113 323.91	4.5	0.46
D		129 520.54	5	0.455
A		0	0	0.601
B	4	97 127.29	4	0.453
C		113 323.91	4	0.448
D		129 520.54	4	0.442

The investment deferral criterion is evaluated using the voltage drop criterion for rural networks and congestion level for urban networks. The idea is to evaluate how much the voltage level can be improved or congestion level can be decreased and therefore the network upgrade can be postponed by setting up MMG, for a given load growth scenario. Likewise, in order to avoid criteria duplication, the environmental criterion can be evaluated as avoided amount of CO_2 emissions due to decreased value of active losses.

As it can be seen from Table I, alternative A prevails against the other alternatives in the cost criterion, whereas, alternative D wins over the rest of the alternatives in the investment deferral criterion and the active losses one.

The assessment described in Table II shows two sources of complexity in the decision making: multiple criteria of evaluation (C_1, C_2, C_3) and multiple scenarios to describe uncertainty (4 scenarios). Our strategy will be first to deal with the multi-criteria problem by conducting the evaluation through trade-off analysis or value function, and then capture the uncertainty issue through robustness analysis.

V. MULTI-CRITERIA ANALYSIS

A. *Trade off analysis*

The methodology behind the multi-criteria framework used in this research considers first trade-off analysis as Decision Aid technique, by defining trade-offs, chosen by the DM after careful examination of the situation. Each trade-off reflects the ratio of improvement in one criterion (for instance, investment deferral) over degradation in another (MMG total cost). Two trade-offs have been defined in this work, namely α_1 [€/year], the trade-off between the cost and investment deferral, which defines the amount of money the MG developer is willing to invest in order to have the network upgrade deferred by one year, and the second trade-off α_2 [€/MW] presenting the amount of money required for having the total active losses decreased by 1MW at peak hour, for each scenario developed.

Starting with indicative value for the cost/investment deferral trade-off of $\alpha_1 = 10000$ [€/year] and for the cost/losses $\alpha_2 = 6000$ [€/MW], the equivalent cost is calculated, using (1).

$$Equivalent\ Cost = C_1 - \alpha_1 \cdot C_2 + \alpha_2 \cdot C_3 \qquad (1)$$

The minus sign before the first trade-off is due to the fact that the term $\alpha_1 \cdot C_2$, presenting the investment deferral, is a benefit.

Table III shows the equivalent cost for each alternative in each scenario, calculated as in (1), after considering the attributes presented in Table II.

It is evident that alternative A wins over the other alternatives in all the scenarios.

TABLE III
TRADE-OFF ANALYSIS AND EQUIVALENT COST FOR EACH SCENARIO AND ALTERNATIVE ($\alpha1$ = 10000 [€/year], $\alpha2$ =6000 [€/MW])

Alternative	Scenario	C1 [€]	α1·C2 [€]	α2·C3 [€]	Eq.cost [€]
A	1	0	0	3709.2	**3709.2**
B		96 696.65	30 000	2977.8	69 674.42
C		112 893.25	40 000	2943	75 836.25
D		129 089.88	40 000	2908.2	91 998.07
A	2	0	0	3604.2	**3604.2**
B		96 696.62	30 000	2895	69 591.62
C		112 893.25	30 000	2861.4	85 754.65
D		129 089.88	30 000	2827.8	101 917.68
A	3	0	0	3709.2	**3709.2**
B		97 127.29	40 000	2795.4	59 922.69
C		113 323.91	45 000	2761.8	71 085.71
D		129 520.54	50 000	2728.8	82 249.34
A	4	0	0	3604.2	**3604.2**
B		97 127.29	40 000	2718	59 845.29
C		113 323.91	40 000	2685.6	76 009.51
D		129 520.54	40 000	2653.8	92 174.34

Now, if a different DM values investment deferral more than the previous one, this attitude is translated in a higher trade-off α_1. For instance, table IV shows the equivalent cost, considering α_1 = 30000[€/year] and α_2 =6000 [€/MW].

TABLE IV
TRADE-OFF ANALYSIS AND EQUIVALENT COST FOR EACH SCENARIO AND ALTERNATIVE ($\alpha1$ = 30000 [€/year], $\alpha2$ =6000 [€/MW])

Alternative	Scenario	C1 [€]	α1·C2 [€]	α2·C3 [€]	Eq.cost [€]
A	1	0	0	3709.2	3709.2
B		96 696.65	90 000	2977.8	9674.42
C		112 893.25	120 000	2943	**-4163.75**
D		129 089.88	120 000	2908.2	11 998.08
A	2	0	0	3604.2	**3604.2**
B		96 696.62	90 000	2895	9591.62
C		112 893.25	90 000	2861.4	25 754.65
D		129 089.88	90 000	2827.8	41 917.68
A	3	0	0	3709.2	3709.2
B		97 127.29	120 000	2795.4	**-20 077.31**
C		113 323.91	135 000	2761.8	-18 914.29
D		129 520.54	150 000	2728.8	-17 750.66
A	4	0	0	3604.2	3604.2
B		97 127.29	120 000	2718	**-20 154.71**
C		113 323.91	120 000	2685.6	-3990.486
D		129 520.54	120 000	2653.8	12 174.34

In this case, the final ranking in every scenario, leads to conclusion that if the investment deferral criterion is valued higher, putting in place MG turns out to be more favorable.

Moreover, the situation is different in each of the scenarios. In the scenarios of high electricity prices, the alternative B wins over the other alternatives, whereas in scenario 1, alternative C gains over the other alternatives, leading to the conclusion that in periods of typical electricity prices, higher percentage of μG installed capacity within the MG makes the MMG concept more favorable. Moreover, in periods of typical electricity prices and 4% load growth (scenario 2), it turns out to be that MG, with the trade-offs from Table IV, is not a favorable concept. However, we will refer again to this discussion in section V-C.

B. Value function approach

The next step is building value function, which joins all the points with the same global value so that the DM is indifferent between two points at the same curve, and completely describes the structure of preferences of the DM.

For the present problem, a general additive value function was considered, for each of the trade-offs defined, as presented in (2).

$$v(c_1,c_2,c_3)=k_1v_1(c_1)+k_2v_2(c_2)+k_3v_3(c_3) \tag{2}$$

The following Individual Value Functions (IVF) were considered:

$$v_1(c_1)=\frac{155000-c_1}{155000-0} \qquad v_3(c_3)=\frac{0.7-c_3}{0.7-0.4} \tag{3}$$

$$v_2(c_2)=\frac{c_2-0}{5-0} \tag{4}$$

Where, c_1, c_2 and c_3 stand for the attributes from table II, for the three criteria considered, total cost, investment deferral and active losses, respectively.

In order to build the Multi-Attribute Value Function (MAVF), as indicated in (2), its parameters or weights need to be assessed (k_1, k_2 and k_3 for the cost, investment deferral and active losses criterion, respectively). When using predefined functions, n-1 judgment of indifference is sufficient to calculate these parameters, where n is the number of criteria. Then, using (2) and considering additionally that the sum of the parameters is the unity, determination of k_1, k_2 and k_3 is immediate. Taking into consideration the trade-offs from table IV, it is possible to define two pairs of points, each point on the same indifference curve, which are valued the same by the DM, assuming that the losses in (5) is the same at P' (C_1, C_2, C_3) and Q' (C_1, C_2, C_3), and therefore it is excluded, as well as the investment deferral in (6):

P' (5000, 0, -) ~ Q' (155000, 5, -) (5)
P'' (153200, -, 0) ~ Q'' (155500, -, 0.4) (6)

Table V presents the weights for each criteria considered.

TABLE V
WEIGHTS FOR THE TOTAL COST, INVESTMENT DEFERRAL AND ACTIVE LOSSES

k1	k2	k3
0.505	0.489	0.006

The same results, in terms of ranking, as the ones in table IV can be obtained, by building the MAVF, as in (2), with the calculated weights from table V.

Value functions are used to capture more complex DM preference structures. Initially, we have considered constant trade-offs, which lead to linear value functions. In order to introduce diversity in the options, experiments with non-linear value functions are needed. In that sense, the investment deferral individual value function is modelled as quadratic function of type (7), whereas the individual value functions of the other two criteria remain as in (3):

$$v_2'\left(c_2\right) = 2\cdot\left(\frac{c_2}{5}\right) - \left(\frac{c_2}{5}\right)^2 \qquad (7)$$

Consequently, the MAVF becomes non-linear, but still additive. In this case, the weights remain the same, which is not a general case. Table VI demonstrates the both linear and quadratic MAVF, whereas Fig. 9 shows graphical representation of the type of quadratic function used for the investment deferral.

TABLE VI
COMPARISON BETWEEN THE LINEAR AND QUADRATIC VALUE FUNCTION

Alternative	Scenario	Linear IVF C₁	 C₂	 C₃	Linear MAVF	Quadr. MAVF
A	1	1	0	0.27	0.507	0.507
B		0.38	0.6	0.68	0.487	0.605
C		0.27	0.8	0.70	0.532	0.611
D		0.17	0.8	0.72	0.480	0.558
A	2	1	0	0.33	0.507	0.507
B		0.38	0.6	0.73	0.488	0.605
C		0.27	0.6	0.74	0.435	0.552
D		0.17	0.6	0.76	0.382	0.500
A	3	1	0	0.27	0.507	0.507
B		0.37	0.8	0.78	0.584	0.663
C		0.27	0.9	0.80	0.581	0.625
D		0.16	1	0.82	0.577	0.577
A	4	1	0	0.33	0.507	0.507
B		0.37	0.8	0.82	0.585	0.663
C		0.27	0.8	0.84	0.532	0.610
D		0.16	0.8	0.86	0.479	0.557

The outcome is much in line with the fact that the MG developer is much concerned at the initial moment when there is a need of network reinforcement rather than after reaching a certain level, when the willingness to pay for extra year of network upgrade deferral, decreases. This can be observed in table VI, where for instance, in scenario 1, alternative B is valued much lower in comparison with alternative C, for the linear MAVF, whereas, for the quadratic MAVF, B gains importance and the difference in respect to alternative C is rather smaller. Moreover, in scenario 3 and 4, alternative D looses value comparing to alternatives B and C for the quadratic MAVF and alternative A is always penalized in the quadratic MAVF in respect to the linear one.

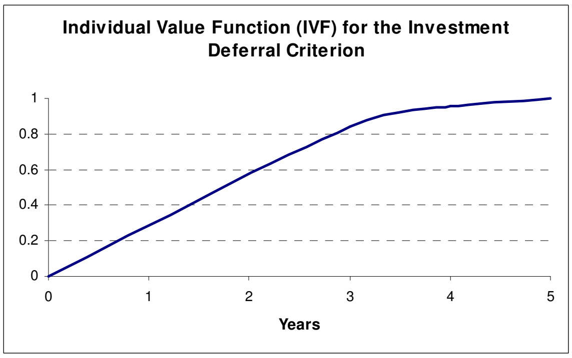

Fig 9. Individual Value Function used for the investment deferral criterion

As it can be seen from Fig. 9, after reaching a certain level of satisfaction, additional increase of years of investment deferral is less valued in comparison to the same additional increase before the satisfaction limit point.

C. *Decision Aid – Dealing with Uncertainties*

The idea of this approach is trying to avoid unpleasant outcomes in adverse scenarios. Two basic concepts has been applied, robustness analysis and analysis of regret. In the robustness approach we are dealing with situations when uncertainties come from competitor's decision. The decision rule corresponds to the minimax paradigm or choosing the alternative that in the worst case has the best value, as in (8).

$$\min_{z\in Z}\max_{s\in S} Robustness(z,s) = \min_{z\in Z}\max_{s\in S}(Eq.Cost(z,s)) \qquad (8)$$

with Z and S being set of alternatives and set of scenarios, respectively.

The regret approach captures situations when the quality of the decision is evaluated ex post. It considers the regret or disappointment of a decision made in respect to a competitor's decision which turns out to be better. Therefore, the best value in each scenario from table IV has been selected, designated as $Eq.Cost^*$ and the regret is calculated, as in (9).

$$\min_{z\in Z}\max_{s\in S} \mathrm{Re}\,gret(z,s) = \min_{z\in Z}\max_{s\in S}(Eq.Cost(z,s) - Eq.Cost^*(s)) \qquad (9)$$

Tables VII and VIII present the results of the two basic concepts, when it comes about uncertainty, robustness and regret, corresponding to the attribute values of table IV. The paradigm behind both approaches is the minimax, i.e. firstly the worse value of each alternative in each scenario is selected, depicted in bold and then the DM preference is made in respect to the best one. Different ranking can be observed for the both approaches, namely in the robustness analysis, alternative A wins over the other alternatives, having globally the best value from the worst ones in each scenario, whereas in the regret approach, alternative B gains over the other alternatives, exploiting the minimum regret in respect to the best value in each of the scenarios.

TABLE VII
ROBUSTNESS ANALYSIS

	Equivalent cost				Robustness
Alternative	Sc.1	Sc.2	Sc.3	Sc.4	Ranking
A	3709.2	3604.2	**3709.2**	3604.2	1
B	**9674.43**	9591.63	-20077.31	-20154.71	2
C	-4163.8	**25754.65**	-18914.29	-3990.49	3
D	11998.1	**41917.68**	-17750.66	12174.34	4

TABLE VIII
REGRET ANALYSIS

	Regret				Min.regret
Alternative	Sc.1	Sc.2	Sc.3	Sc.4	Rankinhg
A	7872.95	0	**23786.51**	23758.91	3
B	**13838.2**	5987.43	0	0	1
C	0	**22150.45**	1163.03	16164.23	2
D	16161.8	**38313.48**	2326.65	32329.05	4

VI. CONCLUSIONS

This paper deals with the evaluation of potential costs and benefits by deployment of the MMG concept using multi-criteria decision aid methods. Within the first part of the work, the potential technical and economic benefits have been assessed using optimization techniques at a MG level, under different scenarios of MG installed capacity and electricity market prices. Furthermore, extending the MG concept into MMG concept, potential cost and benefits coming out of the MMG deployment have been evaluated at the MV level, following different load growth scenarios and electricity market prices. The results lead to more favorable MMG deployment in periods of high electricity prices.

The assessment is made within a multi-criteria framework, using different decision aid techniques. Starting with the trade-off analysis, we have shown how different trade-offs lead normally to different evaluations/rankings in each scenario.

In our analysis, we have used typical MV rural network, leading to some conclusions that the MMG concept deployment is not that favorable, unless we give high importance to the benefits that can come out of the investment deferral. Moreover, we have assumed an equal share of MMG installation costs, in terms of communication and control infrastructure cost, between the consumers and the DNO. If the consumers within the MG recognize and value the overall benefits coming out, thereby having higher share of MG installation cost, it would assumingly lead to different results in the multi-criteria framework.

What can be captured from the studies, performed as a generalized conclusion, is that the problem is rather case sensitive and network dependent.

Nevertheless, we may conclude that the development of the MMG solution becomes interesting in high energy market price scenarios within a specific range of trade-offs.

VII. REFERENCES

[1] MICROGRIDS – Large Scale Integration of Micro-Generation to Low Voltage Grids", EU Contract ENK5-CT-2002-00610, Technical Annex, May 2002.

[2] Antonis G. Tsikalakis, Nikos D. Hatziargyriou, "Centralized Control for Optimizing Microgrid Operation", *IEEE Transactions on Energy Conversion*, vol. 23, No. 1, March 2008.

[3] Hugo A. Gil, Geza Joos, "Models for Quantifying the Economic Benefits of distributed Generation", *IEEE Transactions on Power Systems*, vol. 23, No.2, May 2008.

[4] Hugo A. gil, Geza Joos, "On the Quantification of the Network Capacity Deferral Value of Distributed Generation", *IEEE Transaction on Power Systems*, vol. 21, No.4, November 2006.

[5] A.Tsikalakis, N.Hatziargyriou, "Financial Evaluation of Renewable Energy Source Production in Microgrids Markets Using Probabilistic Analysis*", In proc of the IEEE Power Tech '05* Conference, St. Petersburg June 2005, paper No133.

[6] OMEL electricity market data, available on line http://www.omel.es

[7] Federal Energy Regulatory Commission, "Assessment of demand response and advanced metering", staff report, august 2006.

[8] (2008, Jan. 11). [Online].Available: http://www.hotworkct.com/engineering/alcoa.htm.

[9] G. Pepermans, J. Driesen, D. Haeseldonckx, R. Belmaans, and W. D'haeseleer, "Distributed generation: Definition, benefits and issues," *Int. J. Energy Policy*, vol. 33, no. 6, Apr. 2005.

[10] Internal report, INESCPorto, InovGrid project

[11] Belton, Valerie, Stewart, Theodor J. "Multiple Criteria Decision Analysis: an integrated approach", Boston, Kluwer Academic Publishers, 2001.

[12] Robert. T. Clemen, Terence Reilly, "Making Hard Decisions with Decisions Tools", 2nd rev. ed. Pacific Grove, CA: Duxbury Press, cop. 2001.

[13] Panos Kouvelis and Gang Yu, "Robust Discrete Optimization and Its Applications", Boston, Kluwer Academic Publishers, 1997.

[14] Manuel A. Matos, "Decision under risk as a multicriteria problem", *European Journal of Operational Research*, vol. 181, Issue 3, pp. 1516 - 1529, September 2007.

VIII. BIOGRAPHIES

Julija Vasiljevska was born in Skopje, Republic of Macedonia, in 1982. She received her degree at the Faculty of Electrical Engineering, University Sc. Cyril and Methodius, Skopje. Currently she is pursuing her PhD studies at the Faculty of Engineering, University of Porto, Portugal. Her research interests include optimization of power system operation, including micro-generation, Micro-Grid operation and Multi-Criteria Decision Aid.

J. A. Peças Lopes (M'80–SM'94) received the electrical engineering degree and the Ph.D. degree in electrical engineering from the University of Porto, Porto, Portugal, in 1981 and 1988, respectively. In 1996, he received the Aggregation degree from the University of Porto.

Currently, he is Full Professor in the Department of Electrical Engineering of the Faculty of Engineering of University of Porto. He is also Coordinator of the Power Systems Unit of Instituto de Engenharia de Sistemas e Computadores do Porto (INESC Porto).

Manuel A. Matos (El. Eng., Ph.D., Aggregation, M'94) was born in 1955 in Porto, Portugal. He is with the Faculty of Engineering of the University of Porto (FEUP), Portugal, since 1978 (Full Professor since 2000). He is also coordinator of the Power Systems Unit of INESC Porto. His research interests include classical and fuzzy modeling of power systems, reliability, optimization and decision-aid methods.