Quantification of Economic, Environmental and Operational Benefits of Microgrids

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Abstract-- **Microgrids are Low Voltage distribution networks comprising various distributed generators (DG), storage devices and controllable loads that can operate either interconnected or isolated from the main distribution grid as one controlled entity. The effect of the use of a Microgrid Central Controller (MGCC) to achieve this co-ordinate operation with regards to the potential economic benefits and the power losses avoided in both the local network and the upstream network are presented. Finally, a methodology based on the marginal emissions curve of the upstream network is presented, taking also into account the calculated losses is used for the environmental assessment of the co-ordinate operation of Microgrids. All the above studies have been applied to a typical LV Microgrid interconnected to an actual MV network using actual market prices and DG bids reflecting realistic operational costs.**

Index Terms-- Microgrids, Distributed Generation, Environmental Assessment, Power Losses, Renewable Energy Sources (RES), Markets

I. INTRODUCTION

MICROGRIDS are defined as Low Voltage (LV) or in some cases, e.g. Japan as Medium Voltage (MV) networks with Distributed Generation (DG) sources, together with storage devices and controllable loads (e.g. water heaters, air conditioning) with a total installed capacity in the range of few kWs to couple of MWs. The unique feature of Microgrids is that although they operate mostly interconnected to the upper level voltage distribution network, they can be automatically transferred to islanded mode, in case of faults in the upstream network.

From the grid's point of view, a Microgrid can be regarded as a controlled entity within the power system that can be operated as a single aggregated load [1] and, given attractive remuneration, as a small source of power or ancillary services supporting the network. The installation of DG close to loads will reduce flows in transmission and distribution circuits with loss reduction as a consequence. Microgrids can provide additional benefits to the local utility by providing dispatchable power for use during peak power conditions and alleviating or postponing distribution system upgrades [2]-[3].

They can also provide network support in times of stress by relieving congestions and aiding restoration after faults. From a customer's point of view, Microgrids, similar to traditional LV distribution networks, provide their thermal and electricity needs, but moreover, enhance local reliability [4], and improve some power quality indices by supporting voltage and reducing voltage dips. Power quality impact regarding harmonic distortion, voltage flickers or voltage unbalance have been and are studied and proposed methodology for analyzing, evaluating and proposing ways to combat them are inductively presented in [5]- [7].

This paper describes the results from the simulation of Microgrid's operation under various combinations of realistic market prices and Renewable Energy Sources (RES) production using probabilistic analysis in evaluating the impact of RES operation during the whole year. Also, in this paper attention is focused on the power losses of the specific Microgrid. The presence of a Microgrid generation changes the power flow patterns and therefore both the losses incurred in transporting electricity through transmission and distribution networks and the voltage profile of the buses of the network. The calculation of these voltages is an object of power flow analysis. It is used a program in Matlab environment in order to perform a power flow analysis and the consequent calculation of power losses of the system.

The focus of Section III.C is to estimate the avoided emissions based on the marginal emissions curve of the upstream network, taking also into account the calculated losses that occur in the specific Microgrid.

Moreover, in the study cases of section IV, results from the operation of the Microgrid are presented in Section V for different scenarios of market prices and level of RES production, for the two case studies examined and the two Market policies implemented. The calculations were executed at hourly basis for 12 months using 24 hours time-series for market prices and RES production level. The calculations of the losses were executed for months: January, April, August and October for the MG load peak and valley hour.

Based on the above, some main conclusions can be drawn regarding the quantity of emissions avoidance, losses

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reduction and benefits for the various scenarios studied as presented in the last section of this paper.

II. OPERATIONAL FRAMEWORK

Possible hierarchical control system architecture comprises the following three control levels, shown in Fig. 1 [8]:

- Local Controllers (LC).
- Microgrid System Central Controller (MGCC).
- Distribution Management System (DMS).

Each micro-source and load within the MG is equipped with LC, designated as Micro-source Controller (MC) and Load Controller (LC).

The main interface between the DMS and the Microgrid is the Microgrid Central Controller (MGCC). The MGCC may assume different roles ranging from the main responsibility for the maximization of the Microgrid value and optimization of its operation to simple co-ordination of the local controllers. The information exchange within a typical Microgrid is as follows: Every m minutes, e.g. 15 minutes, each DG source bids for production for the next hour in m minutes intervals. These bids are based on the energy prices in the open market and the operating costs of the DG units plus the profit of the DG owner. The MGCC optimizes the Microgrid operation according to the open market prices, the bids received by the DG sources and the forecasted loads and sends signals to the MCs of the DG sources to be committed and, if applicable, to determine the level of their production. In addition, consumers within the Microgrid might bid for their loads supply for the next hour in same m minutes intervals or might bid to curtail their loads. In this case, the MGCC optimizes operation based on DG sources and load bids and sends dispatch signals to both the MCs and LCs. Fig.2 shows the information exchange flow in a typical Microgrid operating under such conditions.

Two following market policies have been proposed for the operation of Microgrid, described in more details in [9].

- Market Policy 1 where the MGCC aims to minimize the cost of energy for the end-users without selling energy to the grid.
- Market Policy 2, where the MGCC aims to maximize the value of the Distributed Generators (DG) by selling excess energy to the upstream network.

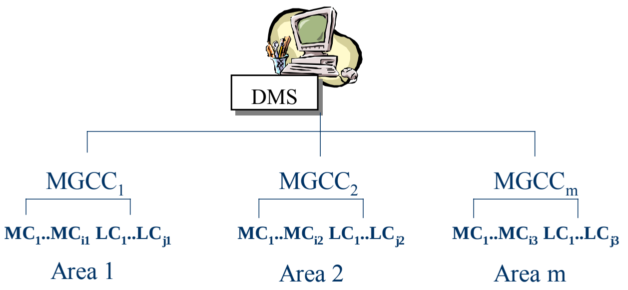

Fig. 1. Hierarchical Control Structure

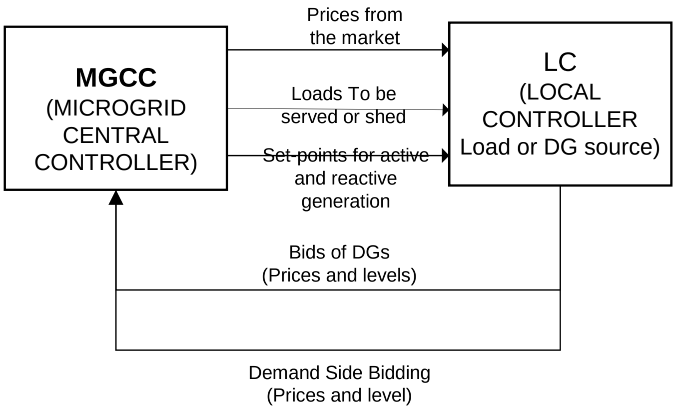

Fig. 2. Information Exchange Diagram

III. METHODOLOGY FOLLOWED

A. Economic Operation

Economic scheduling comprises Unit Commitment (UC) and Economic Dispatch (ED), so that the production of the DG sources, whose outputs can be regulated, and the power exchanged with the grid, are determined.

UC is solved first using a priority list. The DG bids, the load bids, and the market prices are placed in one list according to their differential cost at the highest level of production for the specific period. This list is sorted in ascending bid values, so that the total demand is met.

Linear DG bids are assumed, as presented in (1) according to the cost function of the units, if any, the feedback from the market prices and the requirement for paying back the annual depreciation of the installation cost. In (1) term b_i is expressed in €ct/kWh and c_i in €ct/hour if the unit is to decided to operate. x_i is the output of the units.

$$active\_bid(x_i) = b_i \cdot x_i + c_i \qquad (1)$$

Economic dispatch (ED) is performed next, to determine the output of the regulated sources. The output of the Renewable Energy Sources (RES), i.e. the Wind Turbine (WT) and PV, cannot be regulated and their output is determined by the availability of the primary source, i.e. wind or sun radiation.

If the bids are continuous and convex functions, then mathematical optimization methods can be applied such as the Sequential Quadratic Programming (SQP) utilized in our case [10]. Artificial Intelligence Techniques, like can be also used, especially if scalar or discontinuous bids are considered [11].

B. Power Losses Estimation

Microgrid generation alters the power flows in the network and so will alter network losses. If a small Microgrid generation is located close to a large load then the network losses will be reduced as both real and reactive power can be supplied to the load from the adjacent Microgrid generators. Conversely, if a large Microgrid generation is located far away from network loads then is likely to increase losses on the distribution system. In general there is a correlation between high load on the distribution network and the use of expensive generation plant. Generally, there are active power losses in the transmission network. These losses depend on the currents in the branches of this network which in turn depend on the voltages, and calculating these voltages is the object of the power flow calculation.

The Microgrid generation will generally choose to operate at unity power factor to minimize their electrical losses and avoid any charges for reactive power consumption, irrespective of the needs of the distribution network. If a Microgrid generation produces some power at unity power factor the voltage profile is much more satisfactory [6],[12]. The total injected complex power at bus i, denoted by S_i, is given by: $S_i = P_i + jQ_i = V_i I_i^*$. The summation of powers over all buses gives the total system losses:

$$P_L + jQ_L = \sum_i^n V_i \cdot I_i^* = V_{bus}^T \cdot I_{bus}^* \qquad (2)$$

Where P_L and Q_L are the real and reactive power losses of the system, V_{bus} is the column vector of the nodal bus voltages, I_{bus} is the column vector of the injected bus currents and n is the number of buses.

C. Estimation of Environmental Benefits

Since the Microgrids penetration in the grids is expected to be relatively low, the initial unit commitment schedule of the centralized production is not expected to change. However, there will be modifications in the economic dispatch of the most expensive, i.e. critical units of the upstream network, and the network losses as calculated with the method described above. Both will alter the emissions of the upstream network. Therefore, in order to estimate the emissions avoided, using average yearly or even monthly values will lead to misleading results, since very rarely will the base units be affected [13]. For this reason, the assessment of environmental impact of Microgrids uses a monthly 24-hour typical emissions curve, *Pol,* depending on the upstream network units' characteristics as provided by the following formula.

$$Pol(hr,m,po) = \frac{\sum_{i=1}^{unno} fcu(hr,m)_i \cdot emf(po)_i}{days(m)} \qquad (3)$$

Where, *unno* is the number of the units that may be affected by the introduction of the distributed generation, *fcu* is the frequency that the unit *i* is expected to be the critical unit of the system for the month *mo* and the hour *hr* and *emf* is the emission factor of the pollutant *po* for the unit *i*. The day's number is the number of the days in month *m*.

Typical 24-hour emission curve from the island of Crete for different periods shows the application of (3) in Fig. 3.

The knowledge of hourly marginal units is even more useful when PV installations are foreseen and the production of DER depends on the market prices, as is in our case.

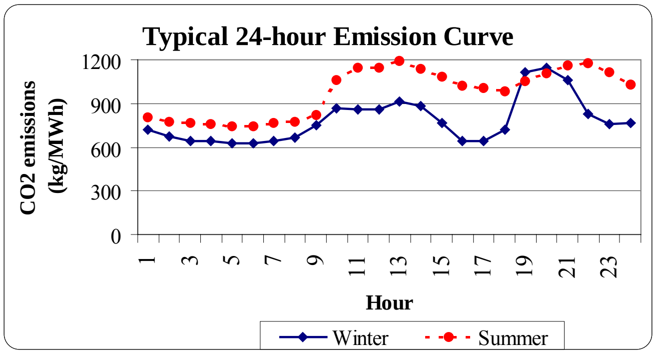

Fig. 3. Typical emission curve from the island of Crete and CO2

IV. CASE STUDY NETWORK

Typical, LV network is used in our study, Fig. 4 [14]. The network comprises three feeders, one serving a primarily residential area, one industrial feeder serving a small workshop, and one commercial feeder. A variety of DER, such as one Micro Turbine (MT), one Fuel Cell (FC), one directly coupled Wind Turbine (WT) and several PVs are installed in the residential feeder. It is assumed that all DER produce active power at unity power factor, i.e. neither requesting nor producing reactive power. Table 1 provides the capacity of the installed DG sources and their fuel costs. Both, Micro-Turbine and Fuel Cell are assumed to run on natural gas, whose efficiency is 8.8 kWh/m^3 and price 10 c€/m^3 [15]. For the MT the efficiency is assumed 26%, while the efficiency of the Fuel Cell is assumed 40% [16]. The corresponding bids submitted are provided in Table II, while emissions data for the fuel consuming units are provided in Table III [17]. For RES the bids are considered as equal to zero reflecting their operating cost. The scope was to calculate the maximum potential savings for the customers in Policy 1 and the maximum income for the Aggregator in Policy 2.

Energy prices from the Amsterdam Power Exchange (ApX) for 2003 [18] have been used to represent realistically the open market in which the LV grid operates. For the monthly demand data, annual demand is distributed to each month according to the Reliability Test System (RTS) weekly variation [19] and the typical demand curve of the Microgrid, is used [14], as well as, monthly demand and production of RES of the studied LV network [13]. Data about the wind velocity time-series of the island of Crete were used and a typical Wind Turbine of 15 kW. The Wind Turbine power curve is represented by a 3rd order polynomial [20]. For PVs, normalized time-series from the PV installation, 1.1 kW, in the campus of the NTUA are used [21].

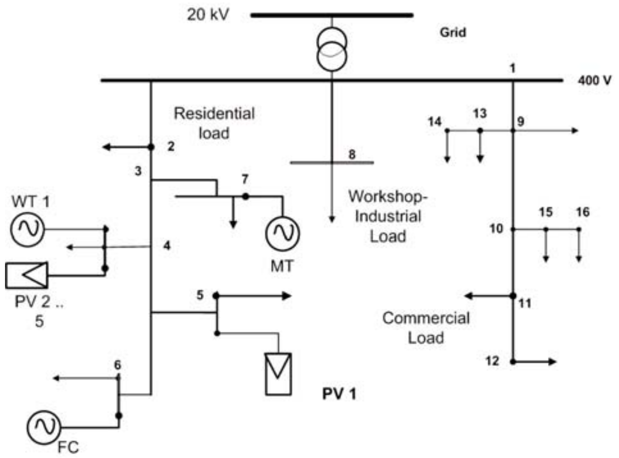

Fig. 4. Information Exchange Diagram

TABLE I
DATA FOR THE CAPACITY OF THE INSTALLED DG UNITS

Unit ID	Unit Name	Min. Capacity [kW]	Max. Capacity [kW]
1	MT	6	30
2	FC	3	30
3	WT	0	15
4	PV1	0	3
5	PV2	0	2.5
6	PV3	0	2.5
7	PV4	0	2.5
8	PV5	0	2.5

TABLE II
DATA FOR THE BIDS CONSIDERED FOR THE INSTALLED DG UNITS

Unit ID	Unit Name	A [Ect/kWh^2]	B [Ect/kWh^2]
1	MT	0.01	4.37
2	FC	0.033	2.41

TABLE III
DATA FOR THE EMISSIONS CONSIDERED FOR THE INSTALLED DG UNITS IN G/KWH

Unit Name	CO_2	NO_X	SO_2
MT	724.6	0.2	0.004
FC	489.4	0.014	0.003

A. Case Studies

Two case studies are examined in this paper, including both Market Policies: Case study 1, comprising the 3 feeders and Case study 2, comprising the residential feeder only for the network of Fig. 4. The following scenarios of operation have been examined regarding the results from the cases studies:

- No DG– sources are considered, i.e. all the demand has been met by the grid.
- Microgrid operation for Market Policy 1 applied.
- Microgrid operation for Market Policy 2 applied.

Combinations of high, average and low market prices with high, average and low RES production level have been considered for each of the studied month, indicating the days with highest, average and lowest wind and PV production and the days with highest, average and lowest electricity prices, according to ApX.

Then the avoided losses in the MV/LV transformer and on the LV lines of the network in Fig.4 can be calculated. The losses for each type of hour are combined with the typical emissions curve to calculate the additional emissions avoided due to losses reduction. In the emissions calculations the reduction of the demand in the network and any emissions by the DGs are taken into account. The results are presented in the coming Section.

V. RESULTS

A. Economic Benefits due to Microgrids

The following sub-sections describe the economic benefits of the Microgrids operation for the two market policies studied for the combinations referred in section IV. If in the Microgrid only RES were installed, then the annual savings by their operation in the market context can be assessed using probabilistic analysis techniques, convolution of expected wind or solar energy with the market prices. The results from such analysis can be used for estimating the period for paying back such an investment. Also, the required subsidy scheme for the timely pay-back time without increasing the operating cost for the Microgrid can be determined. The methodology for such an analysis and representative results from its application with ApX prices are presented in [20].

1) Case Study 1

Since 9 cases have been studied, according to the level of RES production (lowest, average or highest) and the electricity prices according to ApX prices, the final results are shown in Fig. 5-6.

The cost reduction is expressed in terms of percentages in comparison with the first scenario, where no DG sources are considered. The cost difference in absolute values is the income of the Aggregator that the Microgrid has contracted with.

The cost for the both Market Policies is the same as a result of not having sufficient capacity of the MG sources to meet the whole demand and to benefit more selling power to the grid.

Significant cost reduction can be noted for the cases with highest electricity prices, especially for August as a month with highest electricity prices according to ApX prices value (34.68 %– 40.87 % of cost reduction due to the case with no MG sources).

The cost reduction takes the biggest power effect in the cases with highest electricity prices.

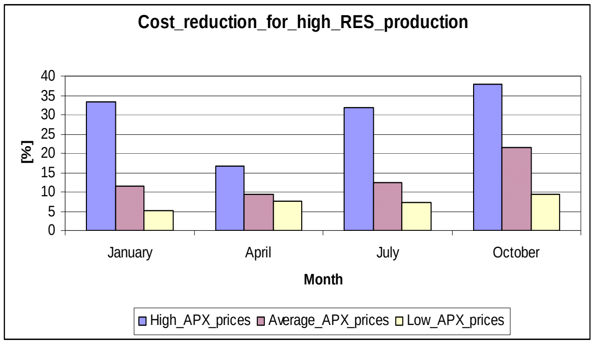

Fig. 5. Cost reduction according to the ApX prices for high RES production for the case study 1

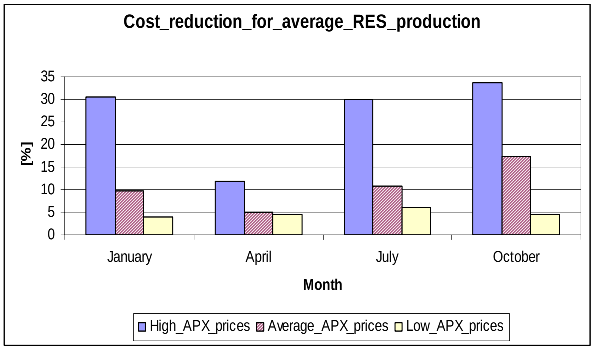

Fig. 6. Cost reduction according to the ApX prices for average RES production for the case study 1

2) Case Study 2

For the case study 2, there is significant additional income for the Aggregator in Policy 2 due to the significantly lower demand compared to the case study 1. Thus the DG capacity is high enough to both meet the demand of the Microgrid and sell active power to the grid. This explains why the cost reduction for the both policies is the same, i.e. the cost reduction difference is zero.

Since 9 cases have been studied according to the level of RES production (lowest, average or highest) and the electricity prices according to ApX prices, the final results are comprised regarding the level of RES production as it follows, Figs 7-9.

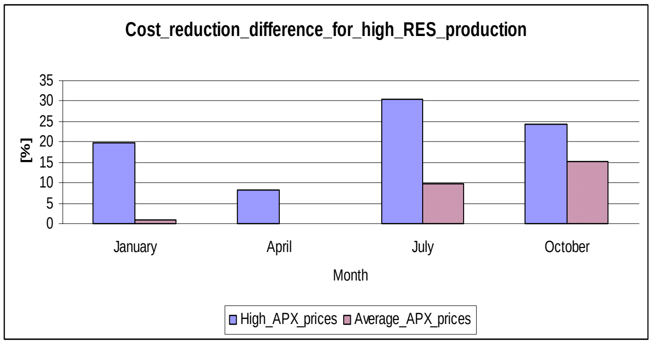

Fig. 7. Cost reduction difference between Policy 1 and Policy 2 for high RES production

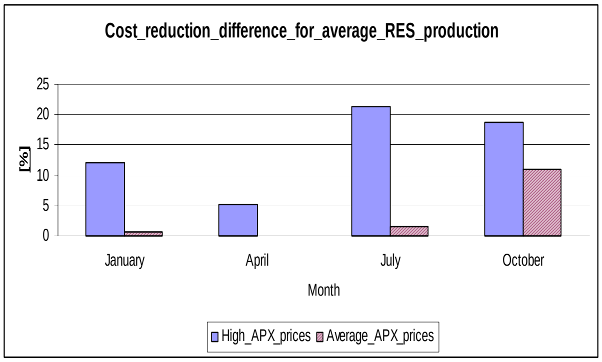

Fig. 8. Cost reduction difference between Policy 1 and Policy 2 for average RES production

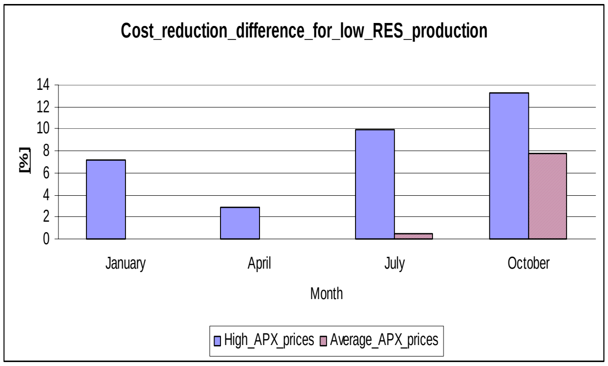

Fig. 9. Cost reduction difference between Policy 1 and Policy 2 for low RES production

It can be noticed that the cost reduction difference between the Policy 1 and Policy 2 is the most significant for high electricity prices, whereas, for low and in some cases for average prices there is no difference in the cost reduction, i.e. no energy is sold to the grid.

The calculations are made for period of 12 months. Selling active power for a few hours a day explains the greater cost reduction in the second market policy due to the first one.

B. Study of the Power Losses

Ten (10) cases have been studied according to the level of RES production (highest, lowest and average) and the electricity prices according to ApX prices. The first case is that where no DG sources are considered. The study has been done for the months January, April, July and October (05:00 in the morning – lowest demand and 19:00 in the afternoon – highest demand).

In this network, the slack bus is at the MV network side while the rest of the network is at LV side. So, practically the total power losses are the power losses from Transformer MV/LV plus the power losses from the LV network.

Characteristic graphical presentations of the results are shown in the following figs 10-12 and tables IV, V.

TABLE IV

JANUARY: $P_{\text{TOTAL LOAD DEMAND, MAX}}$=207.965KW (19:00 IN THE AFTERNOON). SIMILAR RESULTS FOR THE OTHER MONTHS AND HOURS.

Scenarios for January month		Injection From The Grid		Total P_{DG} (kW)	Total Losses P (kW)
		P (kW)	Q (kVar)		
1	Without DG	212.3	5.67	0.00	4.357
2	avg-ApX-avg-RES	141.3	2.75	68.8	2.220
3	avg- ApX -high-RES	144.8	2.85	65.4	2.258
4	avg- ApX -low-RES	148.7	2.97	61.5	2.310
5	high- ApX -avg-RES	141.3	2.75	68.8	2.220
6	high- ApX -high-ES	144.8	2.85	65.4	2.258
7	high- ApX low-RES	148.7	2.97	61.5	2.310
8	low- ApX -avg-RES	172.2	3.88	38.8	3.146
9	low- ApX -high-RES	175.7	4.01	35.4	3.217
10	low- ApX -low-RES	179.7	4.17	31.5	3.308

TABLE V

LV NETWORK'S TOTAL POWER LOSSES REDUCTION (%) FOR JANUARY. SIMILAR TABLES FOR THE OTHER MONTHS AND HOURS.

Scenarios for January month		Total Losses – Reduction (%)			
		$P_{\text{Load, min}}$= 55.201kW		$P_{\text{Load, max}}$= 207.965kW	
		05:00 a.m		19:00 p.m	
		P (Kw)	Q (kVar)	P (kW)	Q (kVar)
1	Without DG	0	0	0	0
2	avg- ApX avg-RES	4.82	5.70	49.1	51.5
3	avg- ApX -high-RES	18.3	24.1	48.2	49.7
4	avg- ApX -low-RES	0.96	1.04	46.9	47.5
5	high- ApX -avg-RES	4.82	5.70	49.1	51.5
6	high- ApX high-RES	18.3	24.1	48.2	49.7
7	high- ApX -low-RES	0.96	1.04	46.9	47.5
8	low- ApX avg-RES	4.82	5.70	27.8	31.5
9	low- ApX -high-RES	18.3	24.1	26.2	29.2
10	low- ApX -low-RES	0.96	1.04	24.1	26.4

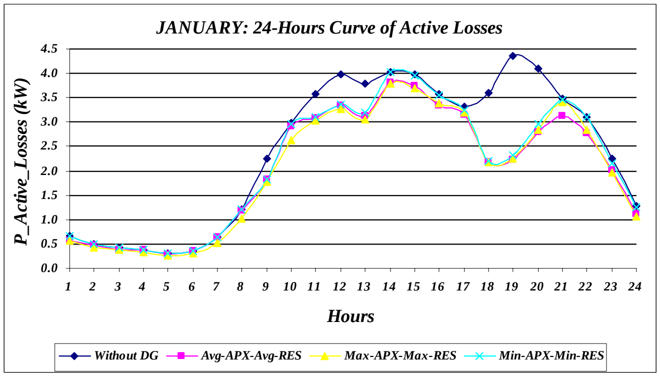

Fig. 10. January: the total 24-hours active losses for some scenarios. Similar graphs for the other months

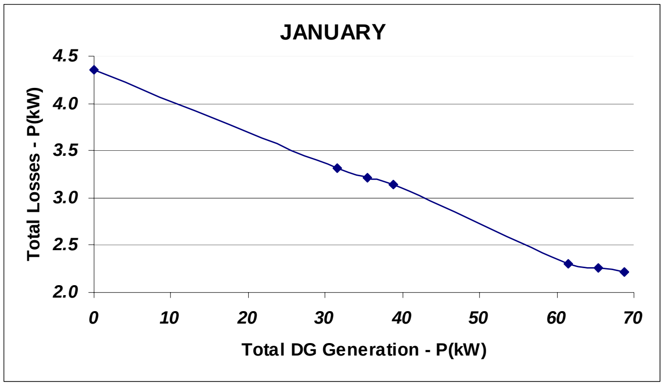

Fig. 11. $P_{\text{Total Load Demand, max}}$=207.965kW (19:00 in the afternoon). Similar graphs for the other months and hours.

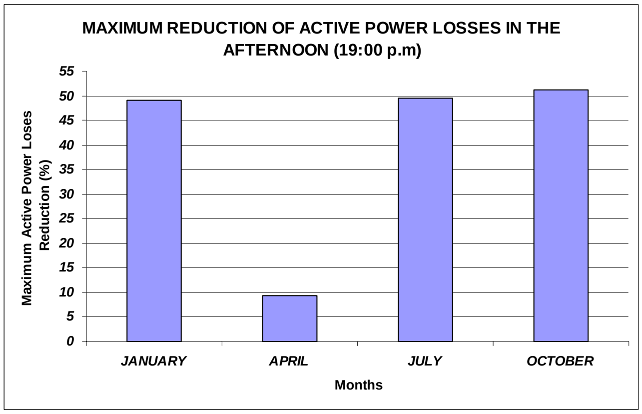

Fig. 12. $P_{\text{Total Load Demand, max}}$=207.965kW (19:00 in the afternoon). Similar graphs for the other months and hours.

C. *Environmental Assessment*

Data from the Hellenic Transmission System Operator (HTSO) for 2006 [22], have been used to derive the 24-hours typical curve for each month. Table VI summarizes the results for the emissions reduction for CO_2 for the studied months. Table VII summarizes the minimum and maximum emission reduction for the rest of pollutants studied.

TABLE VI

SUMMARY OF CO2 EMISSIONS REDUCTION FOR THE STUDIED PERIOD AND MICROGRID.

ApX Prices	RES Production	Emissions reduction [%]	
		min	max
High	High	11.52	13.85
	Average	7.61	9.57
	Low	3.27	6.52
Average	High	8.65	11.26
	Average	6.04	8.81
	Low	2.48	3.24
Low	High	6.56	8.6
	Average	3.92	6.56
	Low	0.12	0.92

TABLE VII

SUMMARY OF PERCENTAGE EMISSIONS REDUCTION(%) FOR THE REST POLLUTANTS.

	NO_X	SO_2	PM-10
min	0.11	0.12	0.13
max	57.15	83.09	61.21

The emissions avoided for the 9 studied scenarios are compared with the emissions emitted due to the demand of the Microgrid without DG sources. Regarding CO_2 the maximum reduction can be achieved during January and max ApX-max RES combination while for the rest of pollutants this is achieved for the same combination during October. The minimum emissions reduction is achieved for combination of low ApX-low-RES during April for all the pollutants studied. The maximum percentage reduction is achieved for SO_2 due to the high sulphur content of the lignite and especially oil-fired units. The emissions reduction is sensitive to the DG penetration but is also very sensitive to the upstream network emissions curve, since DG penetration by itself is not sufficient to explain the difference in the month that maximum emission reduction occurs. For CO_2 the emissions reduction is much sensitive to the RES penetration. This is apparent when comparing low RES production with higher level even at lower prices scenarios, e.g. High ApX-Low RES compared to Low ApX –High RES in Table VI. This is due to the fact that the DG units consuming fuel, especially MT may sometimes present even higher CO_2 levels than the upstream network. Therefore high RES penetration is the other factor influencing the emissions avoidance. For the rest of pollutants this had not been noted due to the fact that the DG units present much lower emission levels compared to upstream network.

D. *Summary of the Results*

Table VIII, IX comprise the cases with high market prices, when the implementation of the Microgrid has the greatest impact, with the both Market policies considered.

TABLE VIII

SUMMARIZED RESULTS FOR CASE STUDY 1 FOR BOTH MARKET POLICIES

Case Study 1			
ApX Prices	RES production	Cost reduction [%]	
		min	max
High	Low	7.61	34.68
High	Average	11.92	38.54
High	High	16.59	40.87
Average	Low	0.7	16.16
Average	Average	3.84	18.44
Average	High	9.2	21.65
Low	Low	0.04	3.08
Low	Average	1.24	6.22
Low	High	5.09	9.35

TABLE IX

SUMMARIZED RESULTS FOR CASE STUDY 2 FOR BOTH MARKET POLICIES

Case Study 2			
Market Policy 1		Market Policy 1	
Cost reduction [%]		Income [%]	
min	max	min	max
19.57	93.93	47.9	117.01
29.9	94.9	35.09	130.02
40.57	95.53	22.41	137.9
1.94	43.57	1.94	43.57
10.7	47.96	11.97	56.46
25.71	54.78	25.71	64.2
0.23	7.71	0.23	7.71
3.44	16.45	3.44	16.45
13.77	23.1	13.77	23.1

For low market prices, however, the cost reduction is rather small, almost negligible for some months with very low market prices and very low RES penetration e.g. April, which shows no incentive for the aggregator of the Microgrid to sell active power to the upstream network in Market Policy 2. Thus, in such market environment, the Microgrid presents common behaviour to the upstream network when either Market Policy 1 or Market Policy 2 is applied.

Furthermore, as it was expected the DG power production reduces the power losses (active and reactive) of the LV network (maximum active power losses reduction 51,13% and maximum reactive power losses reduction 58,41% - October, 19:00 a.m., scenario 6: High RES Production – High ApX Prices). The losses are considerably reduced because the generation is much closer to the load and the lines carry much reduced flows. In addition, the real power injection from the slack bus (bus of 20kV, fig 4) always reduces with DG power production.

VI. CONCLUSIONS

From the above analyses it can be concluded that the cost for the end users is significantly reduced when the demand is met by the Microgrid's units especially for the cases when the electricity prices are very high.

Furthermore, operating cost of a Microgrid can be significantly decreased if DG bids are accepted, especially in networks with high DG penetration that allows selling power to the grid. In such cases network active power quantities can be sold to the main grid increasing the revenues of the aggregator when Market Policy 2 is applied. Implementation of Market Policy 1 involves constrictions of not selling active power to the grid and reducing the production of the DG sources that they can only meet the demand of the μG, although they can produce more and make profit by selling active power to the grid.

Finally, the total active losses of the power system are considerably reduced with DG power production. So emissions savings compared to traditional systems can be achieved especially as the RES penetration gets higher.

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