Centralized Control for Optimizing Microgrids Operation

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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 a controlled entity. This paper describes the operation of a Central Controller for Microgrids. The controller aims to optimize the operation of the Microgrid during interconnected operation, i.e. maximize its value by optimizing production of the local DGs and power exchanges with the main distribution grid. Two market policies are assumed including Demand Side Bidding options for controllable loads. The developed optimization algorithms are applied on a typical LV study case network operating under various market policies and assuming realistic spot market prices and DG bids reflecting realistic operational costs. The effects on the Microgrid and the Distribution network operation are presented and discussed.**

***Index Terms*— Microgrids, Distributed Generation, Demand Side Bidding , Markets, Optimization, Renewable Energy Sources**

I. Introduction

THE deregulated energy environment, among other effects, has favored penetration of Distributed Generation (DG) sources connected near the energy consumers at the Medium Voltage or Low Voltage side of the Distribution Network. These sources comprise several technologies, such as Diesel Engines, Micro Turbines and Fuel Cells either in CHP operation or purely for electricity production, Photovoltaics, small Wind Turbines, Hydro Turbines, etc. The capacity of the DG sources varies from few kWs to 1-2 MWs.

The coordinated operation and control of DG sources together with storage devices, such as flywheels, energy capacitors and batteries, and controllable loads such as water heaters and air-conditions is central to the concept of Microgrids [1,2]. Microgrids mostly operate interconnected to the main Distribution grid, but also islanded, in case of external faults. 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 and, given attractive remuneration, even as a small source of power or ancillary services supporting the network. From a customer point of view, Microgrids similar to traditional LV distribution networks, provide their thermal and electricity needs, but in addition, enhance local reliability, reduce emissions, improve power quality by supporting voltage and reducing voltage dips, and potentially lower costs of energy supply. It is clear that in order to achieve these benefits it is important to provide a coordinated decision making process, in order to balance demand and supply coming both from the DG sources and the MV distribution feeder.

The paper focuses on the functionalities of the Microgrid Central Controller, which is responsible for the optimization of the Microgrids operation. A hierarchical control system architecture comprising three levels [2], is discussed in Section II. Two market policies, including Demand Side Bidding options are presented in Section III and the respective optimization problems are formulated in Section IV. A typical study case Microgrid [3] is presented in Section V and results from the application of the market policies in Section VI. The study case network represents a typical LV feeder with several Distributed Micro sources operating in realistic market conditions and the micro source bids reflect realistic operating costs. General conclusions regarding the economic impacts of this application are drawn in Section VII.

II. Centralized Microgrids Control

A typical Microgrid is shown in Figure 1. The proposed hierarchical control system architecture comprises the following three control levels, shown in Fig. 2 [2]:

- Local Micro Source Controllers (MC) and Load Controllers (LC)
- Microgrid System Central Controller (MGCC)
- Distribution Management System (DMS).

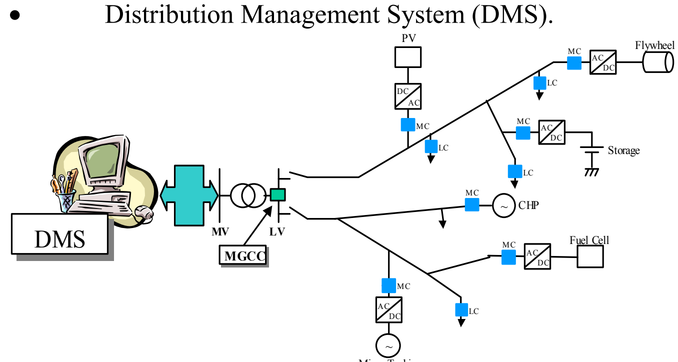

Fig 1 Typical Microgrid Structure

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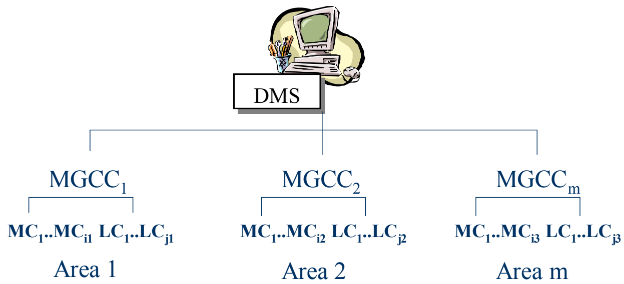

Fig.2. Hierarchical Control Structure

The ***Micro Source Controller*** (MC) takes advantage of the power electronic interface of the DG sources. It uses local information to control the voltage and the frequency of the Microgrid in transient conditions. MCs follow the demands from the Central Controller, when connected to the power grid, and perform local optimization of the DG active and reactive power production, and fast load tracking following an islanding situation. Local Micro *Load Controllers* (LC) installed at the controllable loads, provide load control capabilities following orders from the MGCC for load management.

The ***Microgrid Central Controller*** (MGCC) is responsible for the maximization of the Microgrid's value and the optimization of its operation. It uses the market prices of electricity and gas, costs and probably grid security concerns to determine the amount of power that the Microgrid should draw from the distribution system, optimizing the local production capabilities. The defined optimized operating scenario is achieved by sending control signals to the MCs and LCs. In this framework, non-critical, controllable loads can be shed, when necessary subject to Demand-Side Bidding (DSB). This operation can be considered equivalent to the secondary control of the larger power system. In market terms, the MGCC might represent the functions of an Aggregator or Energy Service provider, who acts in the interest of one or more Microgrids.

Conventional approaches to ***Distribution Management Systems*** (DMS) need to be enhanced with new features related to the operation of Microgrids connected on the feeders. The issues of islanded and interconnected operation of the Microgrids and the related exchange of information with DSB are new important issues, falling outside the scope of this paper.

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 prepared according to the energy prices in the open market, the operating costs of the DG units plus the profit of the DG owner and other needs for the installation facility e.g. space heating. For example, if a DG owner has installed Combined Heat and Power (CHP) unit, may wish to provide heat demand locally at a certain period. For this period, the bids sent to the MGCC should aim in maximizing his profit from participation in the electricity market.

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 3 shows the information exchange flow in a typical Microgrid operating under such conditions.

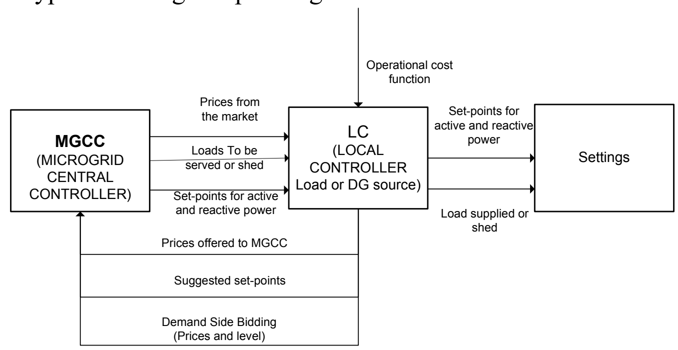

Fig.3. Information exchange flow between MCs and the MGCC

The optimization procedure depends on the Market policy adopted in the Microgrid operation. In the following Section, two possible market policies are described.

III. Participation In Energy Markets

A. Market Policies

In the first policy the MGCC aims to serve the total demand of the Microgrid, using its local production, as much as possible, without exporting power to the upstream Distribution grid. For the overall Distribution grid operation, such a behavior is beneficial, because at the time of peak demand, when energy prices in the open market are high, the Microgrid relieves possible network congestion by supplying partly or fully its energy needs. From the consumers point of view, the MGCC minimizes operational cost of the Microgrid, taking into account open market prices, demand and DG bids. The consumers of the Microgrid share the benefits of reduced operational costs.

In the second policy, the Microgrid participates in the open market, buying and selling active and reactive power to the grid, probably via an Aggregator or similar Energy Service provider. According to this policy the MGCC tries to maximize the value of the Microgrid, i.e. maximize the corresponding revenues of the Aggregator, by exchanging power with the grid. The consumers are charged for their active and reactive power consumption at the open market prices. The Microgrid behaves as a single generator capable to relieve possible network congestions not only in the Microgrid itself, but also by transferring energy to nearby feeders of the distribution network.

B. Demand Side Bidding

It is assumed that each consumer has low and high priority loads allowing him to send separate bids to the MGCC for each type of them. In our application, it is assumed that each consumer places bids in two levels reflecting his priorities. “Low” priority loads can be satisfied in periods of lower prices (shift) or not be served at all (curtailment). Similar approach can be used for more than two bid levels reflecting more precisely the consumer’s priorities. Two options are considered for the consumers’ bids:

A) Shift Option

Consumers place two different bids for the supply of their high and low priority loads in the next operating periods

B) Curtailment Option

Consumers offer to shed low priority loads at fixed prices in the next operating periods.

In both options the MGCC:

- Informs consumers about the open market prices
- Accepts bids from the consumers every m minutes in m minutes intervals for the next hour.
- Runs the optimization routines
- Sends signals to the LCs according to the results of the optimization.

The open market prices only help consumers place their bids. In market policy 1, these prices correspond to the highest energy prices consumers can be possibly charged with . The MGCC optimizes the Microgrid operation according to the bids of both DG and loads.

In the Shift Option, the MGCC sums up the DG sources bids in ascending order and the demand side bids in descending order in order to decide which DG sources will operate for the next hour and which loads will be served. This is shown schematically in Fig. 4. Optimal operation is achieved at the intersection point of the producers’ and consumers’ bids.

In the Curtailment option, consumers bid for part of their load they are willing to shed in the next time intervals, if compensated. The main difference with the Shift Option is that the MGCC knows the current total demand of the Microgrid and sends interruption signals to the LCs, if financially beneficial.

C. Security Issues

Similar to larger power systems, steady state security concerns operation of the Microgrid satisfying voltage constraints and power flows within thermal limits. A critical consideration is the overloading of the interconnection between the Microgrid and the upstream Distribution network. Dynamic security concerns Microgrid operation under a number of contingencies within and above it. For Microgrids, seamless transition between interconnected and islanded mode of operation is of particular importance. Such security considerations can be expressed as additional constraints affecting the optimization outcome [4]. In this paper security is not considered in Microgrid operation. Results from relevant on-going research will be presented in a follow up paper.

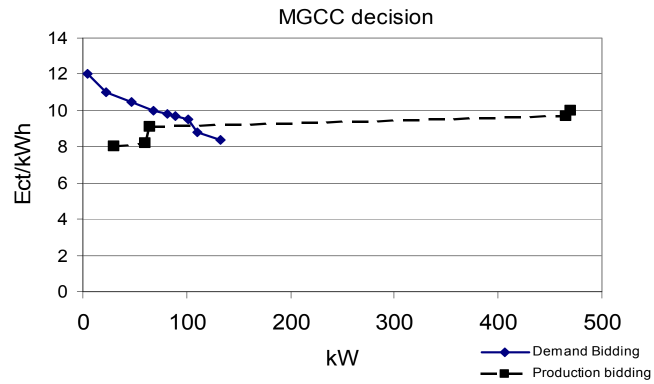

Fig 4. The decision made for the MGCC for shift option

IV. Mathematical Formulation

A. General

The optimization problem is formulated differently according to the market policies assumed. In the following, only active power optimization is considered, since reactive power markets at distribution level are less developed, if any. In any case, extension of the optimization functions to consider reactive power bids is straightforward.

B. Market Policy 1

As discussed in Section II, the MGCC aims to minimize the Microgrid operational cost. It is assumed that the consumers share the benefits. The objective function for each of the m-minutes intervals is:

Minimize{cost} where

$$cost = \sum_{i=1}^{N} active\_bid(x_i) + AX + \sum_{j=1}^{L} load\_bid(y_j) \quad (1)$$

active_bid(x_i) is the bid from the i-th DG source.

x_i is the active power production of the i-th DG source

X is the active power bought from the grid

N, is the number of the DG sources that offer bids for power production.

A is the open market active power price

If Demand Side Bidding is considered, then y_j refers to the bid of the j-th load of the L loads bidding. In the curtailment option the customer is compensated, and this compensation cost load_bid(y_j), is added to the operation cost.

The constraints for this optimization problem are

1) Technical limits of the DG sources, such as minimum and maximum limits of operation.

2) Active power balance of the Microgrid (2). P_demand is the active power demand .

$$X + \sum_{i=1}^{N} x_i + \sum_{j=1}^{L} y_j = P\_Demand \quad (2)$$

C. Market Policy 2

According to this policy, the MGCC (aggregator) maximizes profit from the power exchange with the grid. Consumers are assumed to be charged at open market prices.

The optimization function for each one of the m-minutes intervals is:

Maximize{Revenue-Expenses}= Maximize{Profit}.

In this policy, the MGCC sells energy to the consumers of the microgrid and sells the excess production from the DG sources, if any, to the upstream network at the market price. If the power produced by the DG sources is not enough or too expensive to cover the local load, power X is bought from the upstream network and sold to the consumers, assumingly at the same price. The "Revenue" term is described in (3).

$$\mathrm{Re}\,venue = AX + A\sum_{i=1}^{N} x_i \tag{3}$$

The term "Expenses" includes costs for active power bought from the grid, if any, plus compensation to DG sources. If Demand Side Bidding is considered, relevant costs are added to Expenses as shown in (4).

$$Expenses = \sum_{i=1}^{N} active\_bid(x_i) + AX + \sum_{j=1}^{L} load\_bid(y_j) \tag{4}$$

The MGCC must maximize (5)

$$\begin{aligned} \text{Profit} = A\sum_{i=1}^{N} x_i - \sum_{i=1}^{N} \text{active\_bid}(x_i) \\ - \sum_{j=1}^{L} \text{load\_bid}(bid_j) \end{aligned} \tag{5}$$

The notation in (3)-(5) is the same as the one followed in (1). Constraints are the technical limits of the units and that at least the demand of the Microgrid should be met, as expressed by (6).

$$\mathrm{X} + \sum_{i=1}^{N} \mathrm{x_i} + \sum_{j=1}^{L} \mathrm{y_j} \geq \mathrm{P\_Demand} \tag{6}$$

D. Solution Method

The unit commitment (UC) problem is solved first using a priority list. The DG bids, the load bids, if DSB options are implemented, 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 order, until the total demand is met. The DG bids are assumed linear (7).

$$active\_bid(x_i) = b_i \cdot x_i + c_i \tag{7}$$

For fuel consuming units, c_i represents the hourly payback amount for the investment and b_i is their variable cost, i.e. fuel cost. The term c_i also includes startup costs, only when the unit is not in operation or is still in a start up state.

Renewable Source (RES) based DGs, e.g. WT and PV cannot be regulated and their output is determined by the availability of the primary source, i.e. wind or sun radiation. In order to account for their production in the optimization functions, RES forecasting is required. Indicatively, methods for wind power forecasting, such as [5] and [6] can be utilized. For PV forecasting efforts like the ones presented in [7] and [8] can be used. It should be noted however, that in the scale of a Microgrid, it is important to consider cost effective approaches for forecasting. Today forecasting technology is expensive and forecasting tools are not plug & play ones. It is unlikely for example, that on-line access to meteorological information, required for longer-time (more than 4-6 hours) forecasting will be available at the DG level. Compared to larger installations, the aggregation or smoothing effect is reduced and uncertainty increases, as the size of the Microgrid gets smaller. On this difficulty, one should add the increase in time resolution. A simple technique, that performs admirably well for very-short term forecasting and even outperforms most sophisticated state of the art techniques [8] in high temporal resolution (i.e. 10 minutes) applications is the "Persistence" method. This assumes that the RES production for the next time interval is equal to the current production and can be conveniently used in our application. It is recognized however, that large errors in power forecasting can have a detrimental effect on the economic scheduling of RES dominated Microgrids. For RES, the term b_i stands for the payback amount, i.e each kWh produced is charged according to the annual depreciation of the installation cost.

In all cases the terms b_i and c_i should also consider the expenses for the communication and control infrastructure that is essential for the co-ordinated control of the DGs in Microgrid operation. At the present pace of technological development however, this cost is expected to be only marginal compared to the installation and fuels cost and is not further considered in the analysis.

Economic dispatch (ED) is performed next, so that the production settings of the regulated DG sources, i.e. diesel Units, Microturbines, etc and the power exchange with the grid are determined. The production of the non-regulated DG sources and loads that will not be served has been determined by the UC function. If the bids are continuous and convex functions like in (7), mathematical optimization methods can be used then methods such as Sequential Quadratic Programming (SQP) described in [10]. Artificial Intelligence Techniques can be also used, especially if scalar or discontinuous bids are considered [11,12].

V. STUDY CASE

A typical study case LV network, shown in Fig 5, has been proposed in [3]. The network comprises three feeders, one serving a primarily residential area, one industrial feeder serving a small workshop, and one feeder with commercial consumers. Load curves for each feeder and the whole Microgrid for a typical weekday of October are shown in Figure 6. The total energy demand for this day is 3188 kWh. The power factor of all loads is assumed equal to 0.85 lagging. A variety of DG sources, such as a Micro Turbine

(MT), a Proton Exchange Membrane Fuel Cell (PEM-FC), a directly coupled Wind Turbine (WT) and several PVs are installed in the residential feeder. It is assumed that all DG sources produce active power at unity power factor, i.e. neither requesting nor producing reactive power. Resistances and reactances of the lines can be found in the Appendix-Table A1.

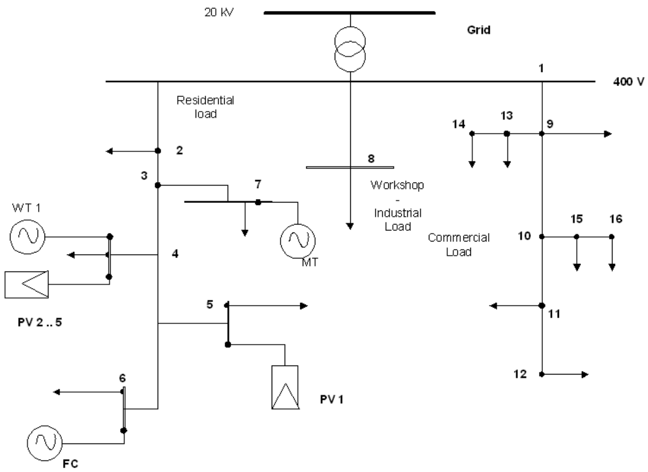

Fig 5 The study case LV Network

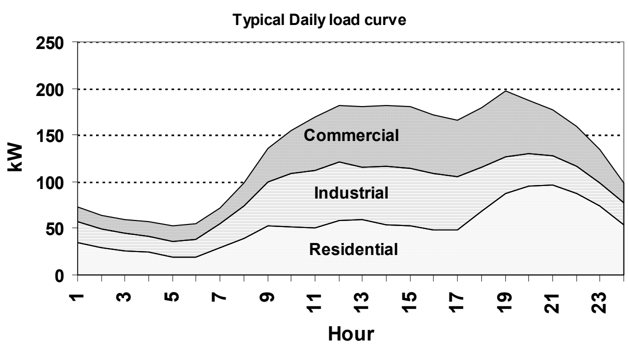

Fig. 6 Typical load curve for each feeder of the study case network

Table I provides the minimum and maximum operating limits of the DG sources. The technical minimum of the MT is obtained from the experiments presented in [13], so that its operation is stable for interconnected operation. Its maximum start up time is slightly above 2 minutes, which is clearly lower than the time step of 15 minutes considered [13]. The PEM FC, the FC type usually used in residential sector installations, also presents fast start up characteristics [14], lower than the time step considered.

Table II summarizes the bids coefficients assumed by the DG sources expressed in cents of Euro (Ect) per kWh and h. In the same table the start up costs, where applicable, are presented. To simplify our analysis, all units in this paper are assumed operating in electricity mode only and no heat is required for the examined period. In order to consider realistic numbers, the electrical efficiency of the fuel consuming units, as well as the depreciation time for their installation have been taken into account, as discussed in the Appendix-Table A2. The calculation of start up costs is also described in the Appendix.

TABLE I
INSTALLED DG SOURCES

Unit ID	**Unit Type**	**Min Power (kW)**	**Max Power (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
BIDS OF THE DG SOURCES

Unit Type	b_i (Ect/kWh)	c_i (Ect/h)	Start up cost Ect
MT	4.37	85.06	9
FC	2.84	255.18	16
WT	10.63	0	0
PV1	54.84	0	0
PV2	54.84	0	0
PV3	54.84	0	0
PV4	54.84	0	0
PV5	54.84	0	0

Normalized data of actual wind power and PV production from a Greek island system (Kythnos) have been considered(Appendix-Table A3). Perfect forecasting of these values is assumed

Finally, actual energy prices from the Amsterdam Power Exchange (ApX) for a day [16] with rather volatile prices have been assumed to represent realistically the open market operation(Appendix-Table A4).

VI. RESULTS

Results obtained from the above analysis show that without DG installations, the actual operating cost for the day considered is 471.83 Euro, and the price per kWh is 14.8 Ect. This is the base case scenario. Tables III and IV provide results for the same day, if the two policies of Section III are simulated. The economic scheduling of the units for this day, is shown in fig 7. It is seen that between 9:00 and 16:00 and during 21:00, the algorithm favors local DG production. For the rest of the time, the DG bids are higher than the market prices and thus MGCC buys active power from the upstream network.

According to the Market Policy 1, the active power prices for the consumers are reduced by 21.53 %. According to the Market Policy 2, the profits for the aggregator are approximately 102 Euros.

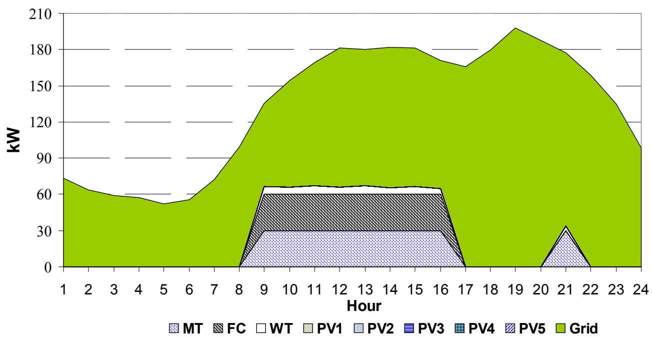

Fig. 7 Daily operation

TABLE III
RESULTS OF MARKET POLICY 1

Cost Euro	Difference with base case	Average Price(Ect/kWh)
370.54	21.53%	11.62

TABLE IV
RESULTS OF MARKET POLICY 2

Revenues Euro	Percentage of Revenues	Average Price(Ect/kWh)
101.28	21.53%	14.8

The effect of Demand Side Bidding is considered next. To simplify the analysis, it has been assumed that all consumers have 2 kW of low priority loads (e.g. an air condition) and the price at which they bid is 6.9 Ect/kWh. This is equivalent to the lowest charge for residential customers in Greece[17]. The rest of the demand is considered of "high" priority and the price for the bid is 8-10 times higher than the "low" priority price. Results for the two market policies and the two load options are presented in Tables V and VI .

TABLE V
RESULTS OF MARKET POLICY 1 WITH DEMAND SIDE BIDDING

	Shift Option	Curtail Option
Revenues (Euro)	308.11	323.89
Load Shed (kWh)	232	232
Cost Reduction (%)	34.74	31.40
Average Price (Ect/kWh)	10.43	10.96

TABLE VI
RESULTS OF MARKET POLICY 2 WITH DEMAND SIDE BIDDING

	Shift Option	Curtail Option
Revenues (Euro)	101.28	101.28
Load Shed (kWh)	232	0
Revenues (%)	21.53	21.53
Average Price (Ect/kWh)	14.8	14.8

It can be seen that in the Market Policy 1, the energy costs are reduced by almost 35 % and 32 % for the shift and curtailment option, respectively, when compared with the base case. Market Policy 2 has no effect on consumer prices, since these are assumed charged at market prices. However, for the shift option, the power exchange with the grid is altered by decreasing the grid demand. This service during hours of stress can be extremely beneficial even for customers that are not part of the Microgrid. It should be noted that in the curtailment option, the optimization routine does not shed any load, since this would reduce the aggregator's profits by the curtailed energy and the related consumer compensation

VII. CONCLUSIONS

This paper deals with the economic evaluation of a typical Microgrid participating in a real-time market following different policies. Bids coming from DG sources and loads are considered. Realistic values for the bids, actual market prices and typical load profiles and renewable productions are used for the simulations. It is shown that under the conditions simulated, the Microgrid operation is economically beneficial leading to either reduced energy prices for the consumers or increased revenues for the aggregator. Moreover, it can be concluded that the aggregation of the DG sources to form a Microgrid under the coordination of a Central Controller can provide optimal co-operation of the production of the DG sources and the energy requested from the upstream Distribution network with mutual economical benefits.

APPENDIX

TABLE A1.
LINES OF THE STUDY CASE NETWORK

Sending Node	Receiving Node	R(pu)	X(pu)
Grid	1	0.0025	0.01
1	2	0.0001	0.0001
2	3	0.0125	0.00375
3	4	0.0125	0.00375
4	5	0.0125	0.00375
5	6	0.0125	0.00375
3	7	0.021875	0.004375
1	8	0.033125	0.00875
1	9	0.0075	0.005
9	10	0.015	0.010625
10	11	0.02125	0.005625
11	12	0.02125	0.005625
9	13	0.010625	0.005625
13	14	0.010625	0.005625
10	15	0.023125	0.00625
15	16	0.023125	0.00625

R and X of the lines have been calculated in power base of 100 kVA and voltage base 400V.

Micro-Turbine and Fuel Cell are assumed to run on natural gas with efficiency 8.8 kWh/m^3 .The fuel price is assumed 10 Ect/ m^3 [18].The Micro-Turbine efficiency is assumed 26% for burning natural gas and the Fuel Cell efficiency is 40% [19]. Data from[19], [20]and [21] have been used to calculate the lifetime of the DG sources and the installation costs. Depreciation times and installation costs are summarized in Table A3. In all cases the interest rate is assumed 8%. The annual cost for each DG unit has been calculated from (8).

$$Ann\_Cost = \frac{i(1+i)^n}{(1+i)^n - 1} \cdot InsCost \tag{8}$$

i is the interest rate, n the depreciation period in years, *InsCost* , the installation cost and *Ann_Cost* is the Annual cost for depreciation.

For the fuel-consuming units, this cost is distributed evenly to their operating hours. For MT and FC it is assumed that they operate for 90% of the year or 7884 hours.

For the RES based DG the annual cost is calculated according to their production. Therefore each kWh produced by these sources should be charged for the annual depreciation of the installation cost. For the WT the capacity factor is assumed 40%, i.e. 3504kWh/kW and for the PVs the yearly production is 1300kWh/kW according to [21].

TABLE A2.
FINANCIAL DATA FOR ESTIMATING THE DG BIDS

	MT	FC	WT	PV
Life-time (years)	12.5	12.5	12.5	20
Costs in Bibliography (Euro/kW)	800-2000	3000-20000	800-5000	4200-10000
Installation Cost (Euro/kW)	1500	4500	2500	7000
Depreciation Time (years)	10	10	10	20
Depreciation cost (Euro/kW-year)	223.54	670.62	372.57	712.92

Start up cost is considered only for fuel consuming units. For the MT, the fuel cost for the start up period at full capacity and half its efficiency has been taken into account to calculate the start up cost. For the FC, the following equation has been used [22] :

$$stp\cos t = a + b\left(1 - e^{-\frac{t_{off}}{\tau}}\right) \tag{9}$$

where a is the hot start up cost, b is the cold start up cost, t_{off} is the time that the FC is switched off and τ is the FC cooling time constant (h). The values considered are a=0.05\$,b=0.15\$ and τ= 0.75h [22]. To simplify our analysis and due to the behavior of function (9), the start up cost considered is equal to a+b=0.2\$ or 16 Ect.

TABLE A3.
NORMALIZED RES PRODUCTION TIME-SERIES

Hour	Wind-power (kW/Installed kW)	PV (kW/Installed kW)
1	0.364	0
2	0.267	0
3	0.267	0
4	0.234	0
5	0.312	0
6	0.329	0
7	0.476	0.002
8	0.477	0.008
9	0.424	0.035
10	0.381	0.1
11	0.459	0.23
12	0.390	0.233
13	0.494	0.318
14	0.355	0.433
15	0.433	0.37
16	0.321	0.403
17	0.329	0.33
18	0.303	0.238
19	0.364	0.133
20	0.373	0.043
21	0.260	0.003
22	0.338	0
23	0.312	0
24	0.346	0

TABLE A4.
PRICES FROM APX ON THE 8TH OCTOBER 2003

Hour	Price Euro/MWh	Hour	Price Euro/MWh
1	22.64	13	149.86
2	19	14	400
3	13.98	15	201
4	12	16	194.99
5	11.53	17	60
6	19.94	18	41.3
7	23.01	19	35.16
8	38.37	20	43.95
9	149.86	21	117.12
10	400	22	54
11	400	23	30
12	400	24	25.57

VIII. REFERENCES

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