NTUA

MICROGRIDS
Large Scale Integration of Micro-Generation to Low Voltage Grids

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WORK PACKAGE C

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Evaluation of the MicroGrid Central Controller strategies

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General Introduction

In work package C the objective is the Development of a Microgrid Central Controller which aims to optimize the operation of the local production either in interconnected or autonomous operation. Within this work package the following functions have been developed :

- Forecasting Tools (short term) for electrical load and heat and for power production capabilities.
- Economic Scheduling, including load shedding and emissions calculations
- Security Assessment
- Demand Side Management (DSM) Functions

These algorithms have been explicitly described in Deliverable DC1 part 1 entitled "MicroGrid Central Controller strategies and algorithms".

Moreover, a flexible software tool for the optimization of the Microgrid operation under steady state security constraints has been developed and described in Deliverable_DC1 Part 2 "Description of software A demo presentation of the capabilities of the software can be found in "***MGCC Demo-Deliverable DC v 2.0.ppt***".

This deliverable is Deliverable DC2 and describes the results from the evaluation of the developed algorithms in typical case study networks. This document consists of two parts ICCS/NTUA Contribution and LABEIN Contribution. Each part contain details about the case studies used and the evaluation results of these case studies.

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ICCS/NTUA CONTRIBUTION

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Table of Contents

1.Introduction

Different scenarios have been simulated for the Microgrids "Study Case LV Network". Two case studies have been derived from this network, the first one with all the three feeders and the other with the residential feeder only. The diagram for the whole Microgrid is given in the Appendix as well as Data about prices, cost functions and renewable power forecasts used in this analysis.
In this study results from the analysis of the impact of Market policies-section 2, Demand Side Bidding Options-section 4, Security and Voltage constraints- sections 3 and 5 are presented as far as operating costs are concerned. Moreover the environmental benefits for Microgrids are presented in Section 6.
In the first 5 sections feed-in tariff structure has been supposed for RES units while in section 7 different scenarios for RES pricing are studied.
The Market policies analyzed are explicitly described in Deliverable DC1 "MicroGrid Central Controller strategies and algorithms" but a small description is also presented here: . In the same deliverable Load options adopted (A and B) are described.

1.1 Short Description of the MGCC operation

The operation of a typical Microgrid is as follows: Every m minutes, e.g. 15 minutes, each DG source bids for its production for the next hour in m minutes intervals. These bids are based on the energy prices in the open market and the costs of each DG unit plus a profit sought for by 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 supply of their loads for the next hour in same m minutes intervals or might bid to curtail their loads, if fairly remunerated. In this case, the MGCC optimizes operation based on DG sources and load bids and sends dispatch signals to both the MCs and LCs. Figure 1.1 shows the information exchange flow in a typical Microgrid.

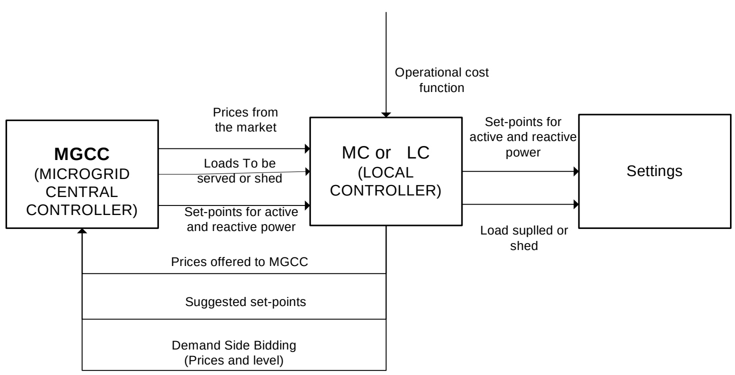


Fig.1.1 *Information exchange flow between MCs and the MGCC*

The optimization procedure clearly depends on the Market policy adopted in the Microgrid operation. In the following paragraphs alternative market policies are described.

1.2 Market Policies

Good Citizen": The Microgrid serves only its own consumers requesting zero reactive power from the grid
In the first Market policy, the MGCC aims to serve the demand of the Microgrid, using its local production, when financially beneficial, without exporting power to the upstream Distribution grid. Moreover, the MGCC tries to minimize its reactive power requests from the Distribution grid. This is equivalent to the "good citizen" behavior. For the overall Distribution grid operation, such a behavior is beneficial, because:

- At the time of peak demand leading to high energy prices, the Microgrid relieves possible network congestion by supplying partly or fully its energy needs.
- The Distribution grid does not have to deal with the reactive power support of the Microgrid, making voltage control easier.

From the end-users point of view, the MGCC minimizes operational cost of the Microgrid, taking into account market prices, demand and DG bids. The end-users of the Microgrid share the benefits of reduced operational costs.
In the second market policy, the Microgrid participates in the energy market of the Distribution area, 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 end-users are charged for their active and reactive power consumption at the 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.
It should be noted that the MGCC may take into account environmental parameters such as Green House Gas (GHG) emissions reductions optimizing the Microgrid operation accordingly.

In this case, MGCC is provided with:

1. The market prices active and reactive power (A Ect/kWh, B Ect/kVarh)
2. The active and reactive power demand (Pdemand, Qdemand), probably as a result of a short term load forecasting tool.
3. The bids of the microgenerators.

Market –policy 2-Ideal Citizen: The Microgrid participates on the market by buying and selling active and reactive power from/to the grid

It is assumed that the Microgrid serves its own needs, but it also participates in the market offering bids via an aggregator. The MGCC tries to maximise the value of the Microgrid, maximising the gains from the power exchange with the grid

The MGCC is provided with:

1. The market price for buying and selling active (A Ect/kWh) and reactive power (B Ect/kVarh) to the grid. The same prices apply to the consumers within the Microgrid.
2. The active and reactive power demand, probably from a short-term forecasting tool
3. The bids of each microsource regarding active and reactive power
4. The maximum capacity allowed to be exchanged with the grid. This can be for example some contractual agreement of the Aggregator or the physical limit of the interconnection line to the grid.

The MGCC provides:

1. Set points of the microsources.
2. Active power X and reactive power Y bought from the grid
3. Active and reactive power sold to the grid.

1.3. Demand Side bidding aspects-Load options A and B

It is assumed that loads at the customers are equipped with load controllers. Each consumer may have low and high priority loads and sends separate bids to the MGCC for each of them. A typical formulation for Demand Side bidding is shown in the figure below :

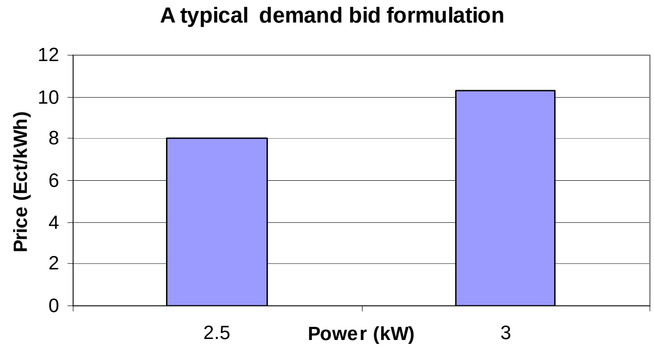


Fig.1.2. *Typical Bid formulation*

Two options have been considered for the consumers' bids:

A) Consumers bid for supply of high and low priority loads

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

In both options the MGCC:

1. Accepts bids from the consumers every hour corresponding to quarter of an hour intervals.
2. Informs each consumer about acceptance of his bids
3. Informs consumers about the prices of the open market. These prices help preparing the bids. For Microgrid operation as a good citizen, the market prices will be the upper bound of prices if steady state security constraints are not considered.

<u>Option A</u>

It is assumed that each consumer places bids for his own load in two levels and the prices of the bids reflect his interest for each load block. The "low" priority loads are the ones the consumer prefers not to operate when the market prices are high, and can be served later, when prices are lower (shift) or not served at all (curtailment). The MGCC knows the total low and high priority loads and decides which of them to serve and which not, based on the optimization function outcome.

In the example of figure 1.2, the consumer has a total demand of 5.5kW=(2.5+3kW). He offers a lower price for a low priority block, such as the water heater.

The MGCC aggregates the demand bids, the production bids and the open market prices and decides which bids will be accepted. The total demand of the Microgrid is the summation of the accepted demand bids. A typical formulation of this procedure is shown in Figure 1.3. In this example the demand of the Microgrid that will be satisfied is 75kW

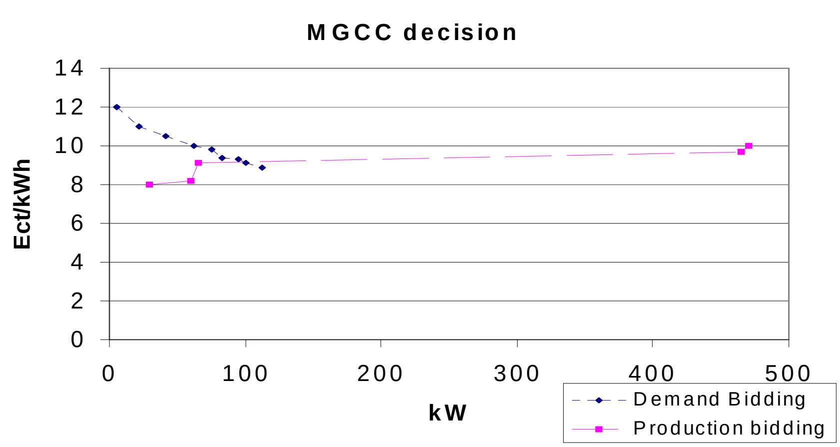


Figure 1.3 *The Decision for the MGCC according to the bidding*

Information about the open market prices influences consumer bids, i.e. might shift load for a while in order to achieve lower costs for his electricity consumption. Short-term load forecasting is less relevant. In this way the total consumption of the consumer is known in advance. Some of the loads will be served and others not, according to the bids of both the consumers and the micro-source producers. For the loads that the MGCC decides not to serve, a signal is sent to the load controllers in order to interrupt the power supply.

Option B

In this case each consumer states the amount of load that can be shed in the next operating period. It is assumed that load can be shed in maximum two steps. The consumer will be compensated for his service, if his bid is accepted. In this option the MGCC has the right to shed “cheaper” loads, if they are on. Loads to be shed are considered as “negative” generation, if they are cheaper than actual generation, lowering the total demand. A typical formulation of the respective bid is described in Figure 1.2. In this example, the consumer states that 2.5 kW is of lower priority and can be shed at 8 Ect/kW, while if the consumer is paid 10.3 Ect/kW he is willing to have all of his demand shed.

2 .Impact of Microsources without DSB and security constraints

2.1 Case study 1 –Three feeders

In this case the load pattern is given from the following table

Table 2.1 Demand for case study 1

Hour	Active Load (kW)	Hour	Active Load (kW)
1	70.663	13	175.511
2	61.331	14	177.848
3	57.376	15	177.028
4	55.745	16	167.358
5	50.705	17	162.077
6	53.936	18	174.144
7	69.93	19	191.028
8	96.183	20	180.202
9	131.316	21	170.208
10	150.543	22	152.49
11	165.353	23	129.023
12	176.727	24	94.677

The following scenarios have been examined :
There are no μ-sources, all the demand has to be met by the grid.
1.The calculated cost is 177.17 Euro
2.Market Policy 1 : The calculated cost is 165.4 Euro
3.Market Policy 2: The calculated cost is 165.4 Euro

The reason that the cost in both Market policies is the same is that the μ-sources have not sufficient capacity to meet the demand and also sell to the grid.
The cost reduction due to the μ -sources is **11.77 Euro** or **6.6%** of the cost. The income for the Aggregator that the MICROGRID has contracted is 11.77 €.

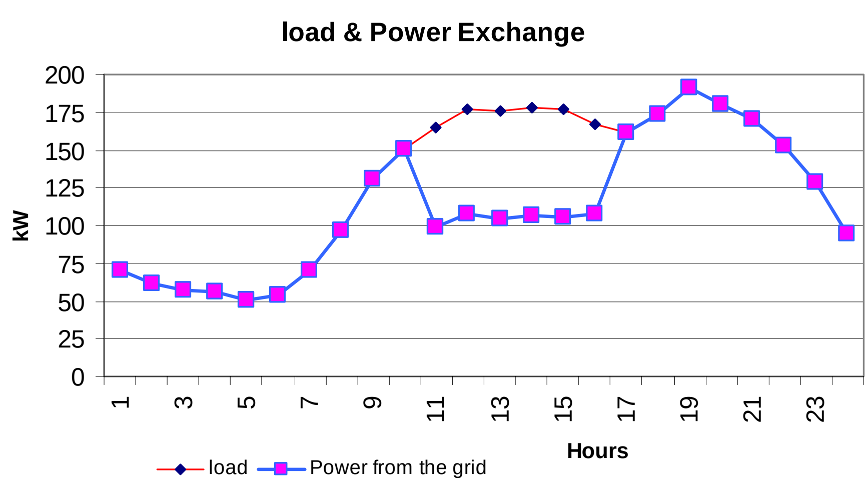


Figure 2.1 *Load and Power Exchange for all three feeders (Market Policies 1 and 2)*

2.2. Case study 2- One feeder :

Only the feeder with the μ-sources – residential consumers is considered as the MICROGRID. The load pattern is given in the following table :

Table 2.2 Demand for case study 2

Hour	Active Load (kW)	Hour	Active Load (kW)
1	32.329	13	54.78
2	26.942	14	49.393
3	24.247	15	48.493
4	22.451	16	44.902
5	17.961	17	44.902
6	17.961	18	62.863
7	26.942	19	80.823
8	35.921	20	88.006
9	48.493	21	88.906
10	47.597	22	80.823
11	46.697	23	68.25
12	53.882	24	49.393

1.There are no μ-sources, all the demand has to be met by the grid.
The calculated cost was **60.13** Euro
2.Market Policy 1 : The calculated cost was **52.74** Euro 12.29% cost reduction
3.Market Policy 2: The calculated cost was **48.91** Euro 18.66% cost reduction
The Income for the Aggregator of the Microgrid is 11.22€.
The load and power exchange in the residential feeder for this policy is shown in figure 2.2. The Negative values mean export to the grid (Hours 11-16). It can be seen that for a few hours a day active power is sold to the grid. These examples show that the cost reduction in the second market policy is greater than in the first case.

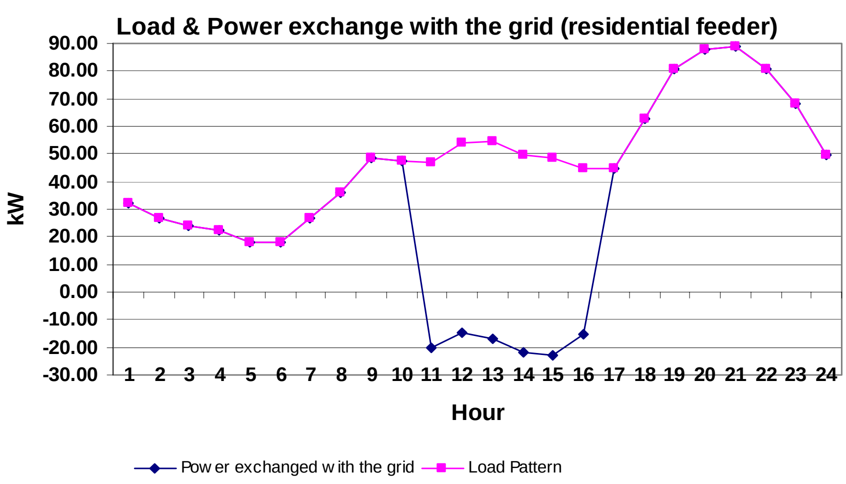


Figure2.2. *Load and Power Exchange for residential feeder (Market Policy 2*)

Table 2.3 Comparative results from Market policy 1 and 2.

	Study Case 1			**Study Case 2**		
Policy	**Grid only**	**Policy 1**	**Policy 2**	**Grid only**	**Policy 1**	**Policy 2**
Cost(€)	177.17	165.4	165.4	60.13	52.74	48.91
Energy Cost **(€ct/kWh)**	5.73	5.35	5.35	5.17	4.53	4.21
Cost Reduction(%)	0%	6.6%	6.6%	0%	12.29%	18.66%

2.3. Ant colony optimization results.

The optimization procedure followed for the Ant colony optimization method is explicitly described in the report "Ant Colony System's (ACS) Optimization of Microgrid Central Controller (MGCC) Operation" by J.Vlachogiannis and in Deliverable DC1 "MicroGrid Central Controller strategies and algorithms".

When there are no μ-sources, all the demand has to be met by the grid and the calculated cost is 60.13 €.
When the μ-sources are in operation:
Since the ACS algorithm optimizes discrete problems and the settings of the μ-sources have been discretized there is a minor error in the load satisfaction. This error is penalized as an extra-cost is added in the total calculated cost. The total penalized cost over the planning period is **53.47 €** providing **11.11%** cost reduction for market policy 1.

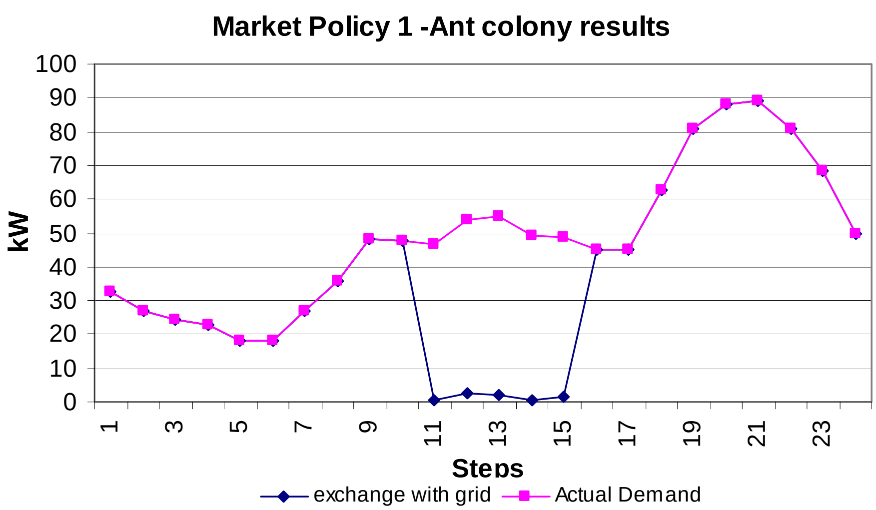


Figure 2.3. *Ant colony method results for residential feeder*

The total penalized cost for the Microgrid under Market Policy 2 is calculated at **49.3 €** providing **18.01%** cost reduction. The income for the aggregator of Microgrid is 10.83 €. In this case energy is sold to the grid from 11th to 16th hour of the period as figure 2.4 depicts.

Total penalized cost of Microgrid = Cost of Microgrid + Error Cost **= 49.3€**

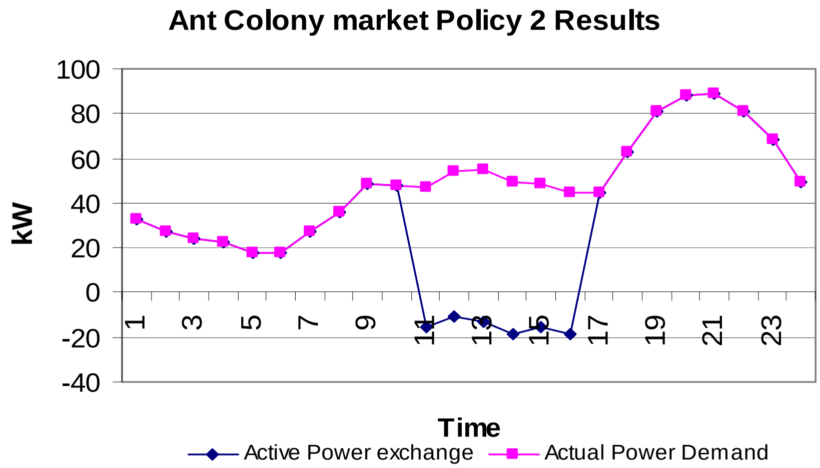


Figure 2.4. *Ant colony method results for residential feeder*

2.4 Conclusions

From the analysis in sections 2.1 to 2.3 it can be concluded that the operating cost of a Microgrid can be significantly decreased when DG bids are accepted. The cost reduction is greater in networks with lower demand. In such network active power can be sold to the main grid increasing the revenues of the aggregator if Market Policy 2 is applied. The constraint of not selling active power to the network when market policy 1 is followed reduced the production of DG sources to producing the necessary active power for meeting the demand only although it would be profitable to sell active power to the network.

3. Steady state Security impact–Results

If steady state security issues like adequacy are taken into account then the operating cost is modified as table 3.1 shows:

Table 3.1 Comparative results from Market policy 1 and 2 with steady state security constraints.

	Study Case 1			**Study Case 2**		
Policy	**Grid only**	**Policy 1**	**Policy 2**	**Grid only**	**Policy 1**	**Policy 2**
Cost(€)	177.17	175.47	175.47	60.13	67.18	63.16
Energy Cost (€ct/kWh)	5.73	5.68	5.68	5.17	5.77	5.43
Cost Difference(%)	0%	-0.96	-0.96	0%	11.72	5.04
Increase in cost due to steady state security constraint		6.09%	6.09%	0	27.34%	29.14%

In the 1st case study the Aggregator for the Microgrid(Policy 2) earns 1.7 € decreasing his revenues by 85.47% whereas in the second one loses 3.03€. decreasing his revenues by 127% As it can be seen from the diagram below there is a slight modification in the power exchange due to the fact that some μ-sources are committed in order to meet the steady state security constraints.

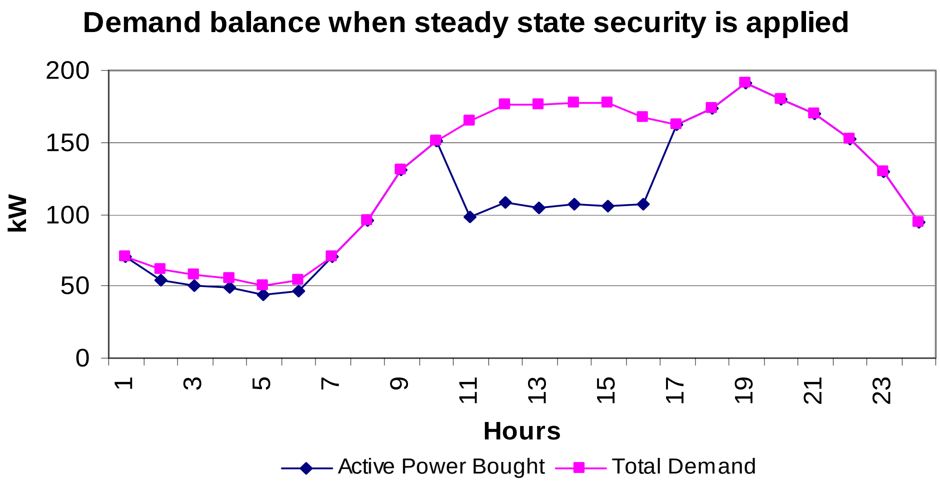


Figure 3.1 *Demand balance when steady state security is applied, case study 1*

For case study 2 , if Market Policy 2 is applied then active power is sold to the grid.

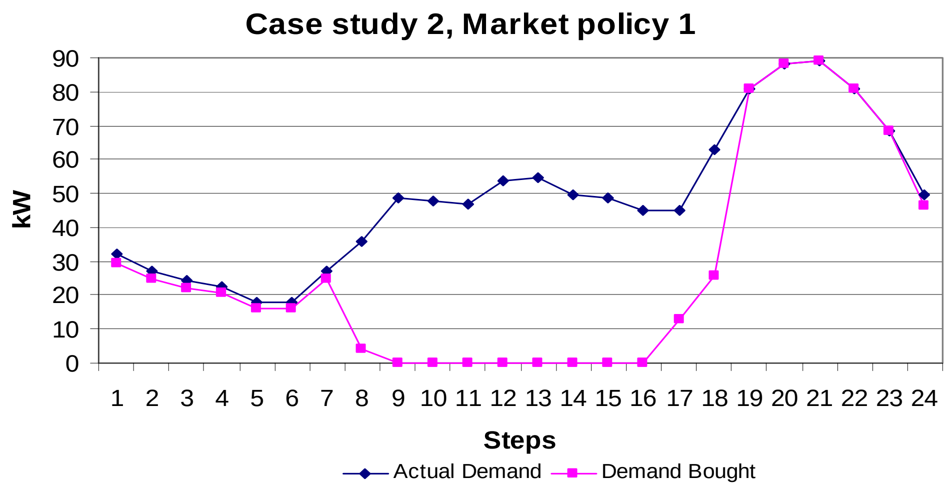


Figure 3.2 *Demand balance when steady state security is applied for market policy 1*

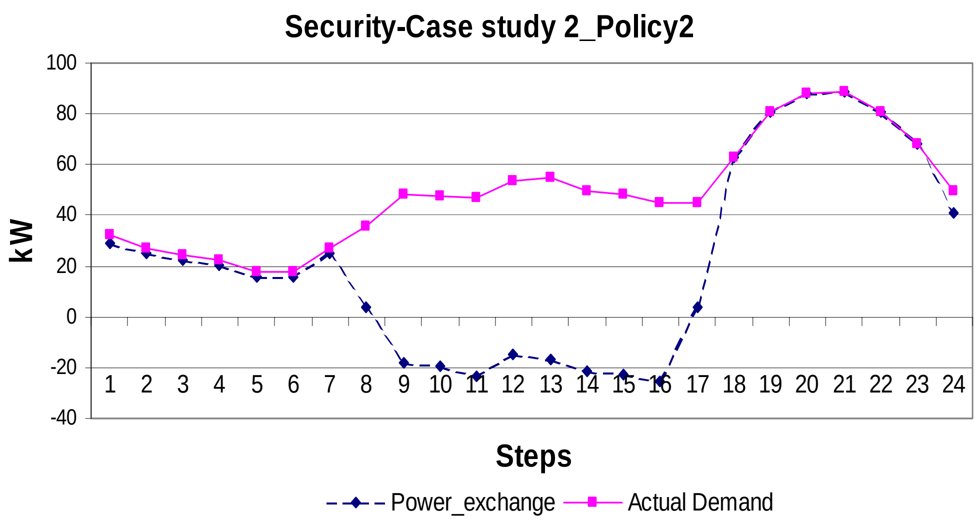


Figure 3.3 *Demand balance when steady state security is applied-Market policy 2*

3.1 Conclusions

It can be concluded that steady state security constraints increase the operating cost although the final operating cost can be lower than the operating cost without microsources as it is for case study 1 .The increase is higher in lower capacity networks –study case 2 where the aggregator may even lose money if market policy 2 is applied. The committed units are dispatched at their technical minimum during periods of low market prices in order to decrease the effect of the high bid rate. Therefore the lower the technical minima of the committed units the lower the increase in the operating cost.

4. Results from the application of DSB options

It is assumed that the low priority bid for the customers is 6.8 Ect/kWh, that is the lowest charge for the residential consumers in Low Voltage grids in Greece.
The bids for each step of the optimization horizon are shown in the following table. The same bids were used for every scenario run :

Table.4.1 Total demand bids- Case study 1

Hours	Total Demand bids for shedding (kW)	Hours	Total Demand Bids for shedding (kW)
1	18	13	26
2	16	14	26
3	16	15	26
4	18	16	26
5	18	17	26
6	18	18	26
7	18	19	26
8	20	20	26
9	24	21	26
10	26	22	26
11	26	23	24
12	26	24	24

Table.4.2 Total demand bids- Case study 2

Hours	Total Demand bids for shedding (kW)	Hours	Total Demand Bids for shedding (kW)
1	6	13	10
2	6	14	10
3	6	15	10
4	6	16	10
5	6	17	10
6	6	18	10
7	6	19	10
8	6	20	10
9	10	21	10
10	10	22	10
11	10	23	10
12	10	24	10

4.1 Results from option A demand side bidding-Policy1

First the case of shedding only the low priority loads, if the bid values are rather low was examined
The rest of the demand–high priority loads -is met by both the μ-sources and the grid in an optimal way. The demand met and the demand shed are shown in table 4.3. Other values for the demand side bidding can be obtained taking into account historic values of the open market prices.

The total demand shed is 156 kWh reaching 5.04% of the total MICROGRID demand.
In this case the operational cost of the MICROGRID is 150.15 €, and therefore the cost is reduced by 15.25 € or 9.22% compared to no DSB case .

Table 4.3 Load shed and met for case study 1

Hours	Demand Met (kW)	Load Shed (kW)	Hours	Demand met (kW)	Load Shed (kW)
1	70.663	0	13	149.511	26
2	61.331	0	14	150.214	26
3	57.376	0	15	151.028	26
4	55.745	0	16	141.358	26
5	50.705	0	17	162.077	0
6	53.936	0	18	174.144	0
7	69.93	0	19	191.028	0
8	96.183	0	20	180.202	0
9	131.316	0	21	170.208	0
10	150.543	0	22	152.49	0
11	139.353	26	23	129.023	0
12	150.727	26	24	94.677	0

The cost per kWh for each hour of the optimization horizon is depicted in the following diagram 3.1

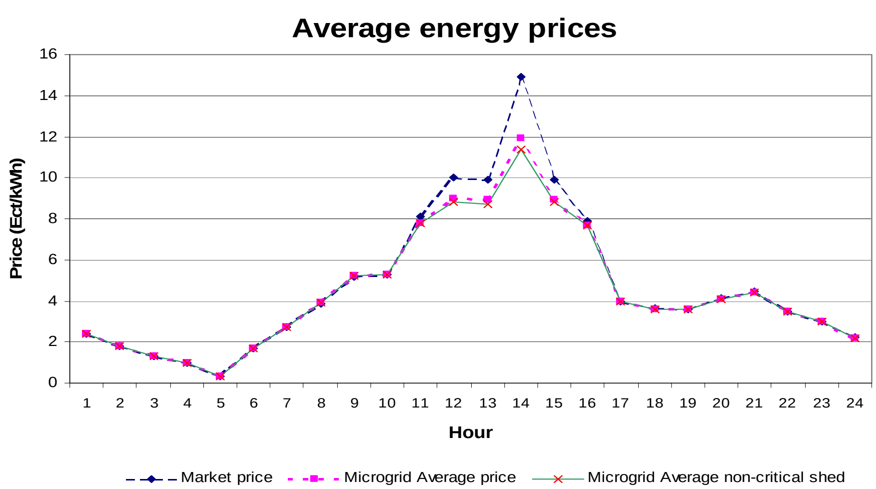


Figure 4.1 *Average energy prices*

The average value is 5.13 Ect/kWh ,4.11% lower than the case of policy 1.The maximum price is 11.4 €ct/Kwh at the 14th hour compared to 11.9€ct/kWh without DSB and 14.9Ect/Kwh of the open market prices.

Case study 2

Due to DSB and the low load there are intervals that the Microgrid can operate without buying electricity from the grid. The energy demand shed is 60 kWh(5.13% of the demand) and is distributed to the intervals according to table 4.4. The operating cost in such a case is 49.5 €, 6.14 % lower than the case without DSB.The active power balance in such a case is described in figure 4.2.

Table 4.4 Load shed and demand met- Case study 2

Hours	Demand Met (kW)	Load Shed (kW)	Hours	Demand met (kW)	Load Shed (kW)
1	32.329	0	13	44.78	10
2	26.942	0	14	39.393	10
3	24.247	0	15	38.493	10
4	22.451	0	16	34.902	10
5	17.961	0	17	44.902	0
6	17.961	0	18	62.863	0
7	26.942	0	19	80.823	0
8	35.921	0	20	88.006	0
9	48.493	0	21	88.906	0
10	47.597	0	22	80.823	0
11	36.697	10	23	68.25	0
12	43.882	10	24	49.393	0

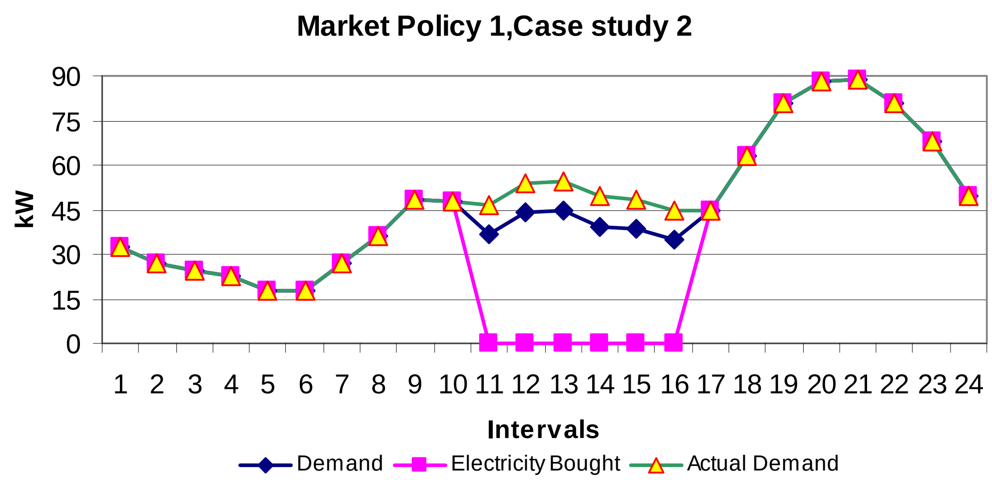


Figure 4.2 *Power exchange when Load option A is applied*

4.2 Results from option B demand side bidding-Policy1

The load shed in this case will be the same as in the previous case but the Aggregator has to pay the consumers for shedding their loads. In such a case the cost is by (6.8Ect/kWh*156kWh),= 10.61€ higher reaching 161.21 €, 2.53% lower than the case of not having DSB.
This cost will be paid by the end users. The average electricity price will be 5.49 Ect/kWh, that is higher than the average cost of policy 1.
In case study 2 the cost would have been higher by (6.8 €ct*60kWh)=4.08 € reaching 53.58€, that is 1.6% more expensive than the operation without DSB due to the fact that the load shed reduces the output of the running units compared to no DSB case.

4.3 Results from market Policy 2 and Load Option A.

In this case the bids of the customers are compared to the open market prices, since the aggregator sells at that price the active power to them. In such a case there is no modification in the revenues of the Microgrid Aggregator compared to no DSB case, since if active power is not sold to the Microgrid consumers, it will be sold to the grid . Therefore, the results as far as the revenues calculated are concerned remain the same as in no DSB case,11.77€ . However, the load exchange with the grid is modified as the following diagram depicts. The active power bought from the grid is lower when there is DSB, by the amount of the demand shed. The total demand shed is 156kWh.

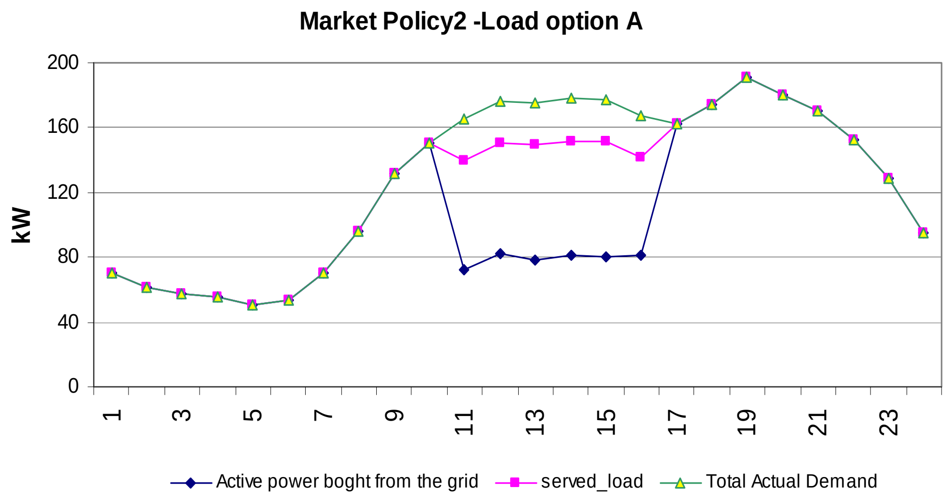


Figure 4.3 *Power exchange when Load option A is applied*

If this load option is applied to the residential consumer only, the power exchange is shown in figure 4.4 In this case 60 kWh have been shed and 171.43 kWh have been sold to the grid. The income for the MGCC aggregator remains the same as with the case without DSB.

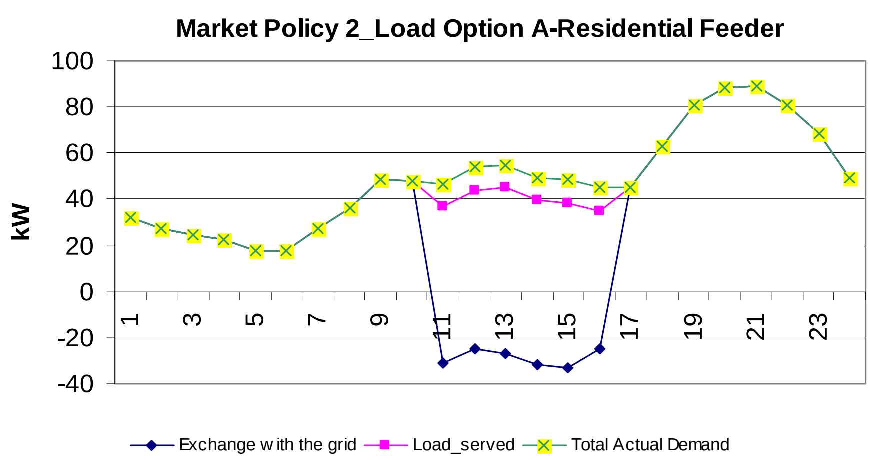


Figure 4.4 *Active power balance for the* 2^{nd} *case study when Market policy 2 is applied and load option is adopted.*

4.4 Results from market Policy 2 and Load Option B

In this case the Aggregator does not only have to pay for the μ-sources production but also for the loads that are going to be shed. The active power produced by the μ-sources will be sold either to the Microgrids consumers or to the grid at the same price.. Therefore, if the load bids are accepted, the income for the Microgrid aggregator will be the same but his expenses will be increased. Hence, there is no incentive for the aggregator to accept DSB offers unless either the price the Microgrids customers are charged with is lower than the open market prices or there is any security constraint. The only reason for an aggregator to accept a load bid is that the amount bid_price+open_market_price is lower than one of the bids of the μ-sources, and instead of committing that μ-source ,the aggregator prefers to shed load paying the bid_price

Tables 4.5 and 4.6 summarize the results from the above analysis.

Table4.5 Summarizing costs for DSB without security constraints

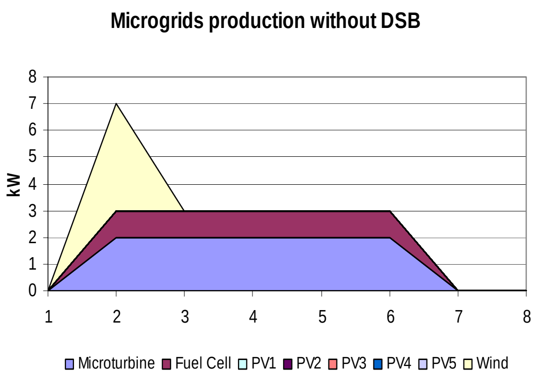
	Policy 1 – Option A	Policy 1 –Option B	Policy 2 –Option A	Policy 2 – Option B
Change in Cost /revenues compared to no DSB	-15.25€ -9.22%	-4.19€ -2.53%	0€ –0%	0€
Cost Reduction /revenues compared to actual operation	27.01€ 15.25%	15.96€ 9%	11.77€-6.6%	11.77€-6.6%

Table 4.6 Summarizing costs for DSB without security constraints <u>CASE STUDY 2</u>

	Policy 1 – Option A	Policy 1 –Option B	Policy 2 –Option A	Policy 2 – Option B
Change in Cost /revenues compared to no DSB	-3.24 € -6.14%	0.84 € 1.6 %	0€ –0%	0€
Cost Reduction /revenues compared to actual operation	10.63€ 17.68 %	6.33€ 10.52 %	11.22€ 18.66%	11.22 € 18.66%

<u>4.5 Results from market Policy 1 and load Option A when steady state security constraints are concerned.</u>

In this case the MGCC tries to meet the steady state security constraints not only by committing μ-sources when they are capable of meeting the demand but also by creating a list of the loads that can be shed in case of an emergency. Thus the MGCC tries to meet the total demand of the MICROGRID committing the necessary μ-sources and proposing loads for shedding. By providing this ability in case of emergency, the number of units needed to be committed are reduced. The cost reduction in such a case is 1.95 € ,slightly higher than in the case of the steady state security constrained solution without DSB, since only during one hour one unit has not been committed compared to section 3 as shown in Figure 4.5. The demand shed in an emergency case can be found in table 4.7



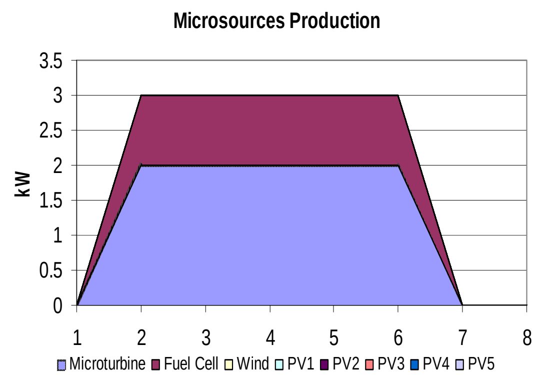


Figure 4.5 *Microsources production with and without DSB when security constraints are applied.*

If the security constraint does not apply for the total demand but only for the "high" priority loads then the MGCC tries to commit the necessary μ-sources in order to meet, if possible, the demand of these loads in case of an emergency. This means that the number of necessary μ-sources for meeting this constraint are reduced and thus the operating cost.

Moreover instead of simply viewing whether the system can be secure or not as in figure 4.6 it can be shown in the screen how much is the possible shedding of active power in case of the grid disconnection in two cases.

a) The low priority loads bidding are accepted
b) There are not priority loads.

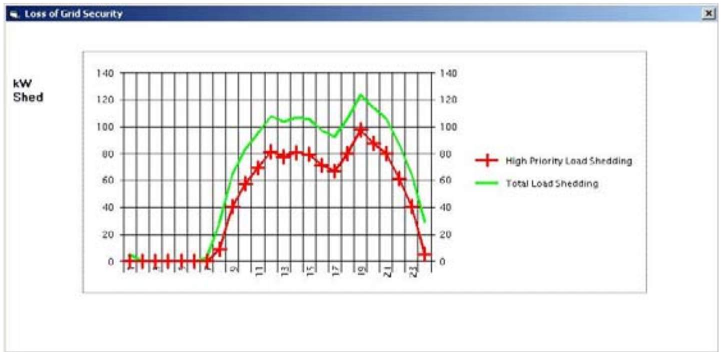


Figure 4.6. *The screen that shows the active power to be shed in case of grid disconnection*

The red line is the demand that is going to be shed even if the low priority loads have been shed. The green line shows the total demand shed in case of grid disconnection.

Table 4.7 Demand shed in emergency when steady state security constraints are applied, case study 1

Hours	Demand shed only in emergency (kW)	Hours	Demand shed only in emergency (kW)
1	0	13	0
2	16	14	0
3	16	15	0
4	18	16	0
5	18	17	0
6	18	18	0
7	18	19	0
8	0	20	0
9	0	21	0
10	0	22	0
11	0	23	0
12	0	24	0

If loads with bid values lower than the open market prices are shed as in operation without constraints then the operating cost will be 163.21 €, with the demand shed in an emergency according to table 4.7 and the rest of demand shed as in Table 4.3. This means 8.7% more expensive compared to the solution without security constraints but 6.87 % lower cost compared to security constrained operation without DSB. The electricity balance is shown in figure 4.7. The demand shed is as in no security constraint case.

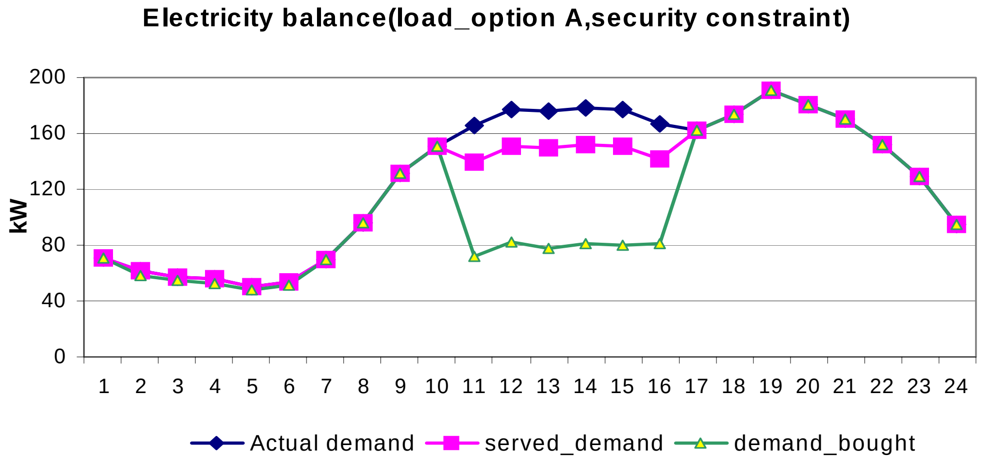


Figure 4.7 *Active power balance for the 1st case study when load option is adopted with security constraints*

Case study 2

In this case the operating cost is 63.13 € that is lower than the case without DSB as expected. The electricity balance in such a case is shown from the diagram below(Figure 4.8). During the 23rd hour the system can be secure if the loads offered by DSB are shed in the case of emergency, that is why the power exchange is reduced.

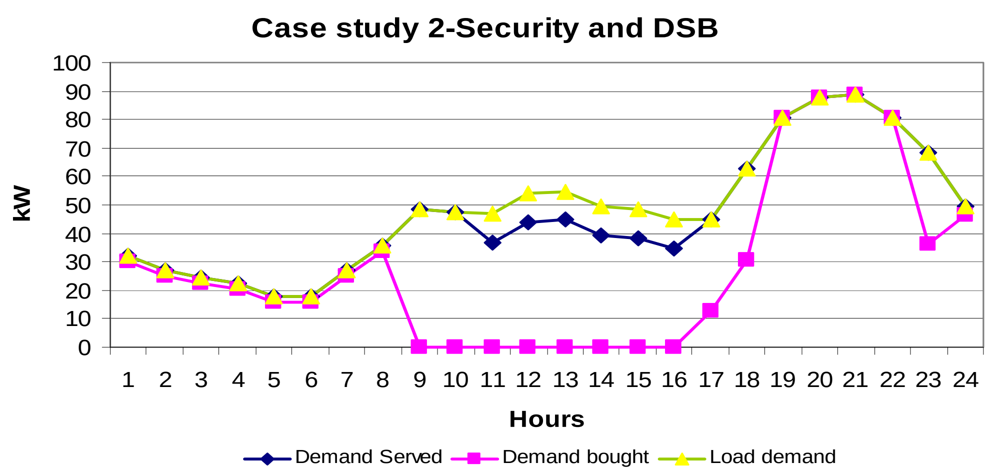


Fig 4.8 *Case study 2 security and DSB with Market Policy 1.*

Table 4.8 Demand shed in emergency when steady state security constraints are applied, Case study 2

Hours	Demand shed only in emergency (kW)	Hours	Demand shed only in emergency (kW)
1	6	13	0
2	6	14	0
3	6	15	0
4	6	16	0
5	6	17	0
6	6	18	0
7	6	19	0
8	6	20	0
9	10	21	0
10	6	22	0
11	0	23	10
12	0	24	0

4.6 Results from market Policy 2 and load Option A when steady state security constraints are concerned.

As in the case with Policy 1, DSB can help in reducing the operating cost of the Microgrid increasing the revenues of the aggregator of the Microgrid. If the open market price is higher than the DSB value, this load will be shed. Otherwise, if any demand side bid is lower than the μ-sources bids and the Microgrid can be adequate , this demand bid will be accepted but the load will be shed only in case of emergency. However, in such a case the operating cost will be lower since some μ-sources more expensive than the demand side bidding will not be committed.
In case the DSB is used only for cases of emergency and not for the normal interconnected operation then the units to be committed to meet the adequacy constrained are reduced as described in section 4.5 and the revenues for the MGCC aggregator are 1.95 €, slightly higher than in the case of the steady state security constrained solution without DSB.
If the DSB option is applied not only for the security operation but also for shedding load to avoid high charges then the demand shed is described by table 4.7.The revenues for the aggregator is in this case is 1.95 Euro since the demand shed is not bought from the grid. Figure 4.7 describes the electricity balance in such a case.
If market policy 2 is applied for case study 2, then active power is sold to the grid for some hours (9-16). The demand shed is the same as with Market policy 1 but it is financially beneficial to increase the production of the DG sources so that active power is sold to the grid. The income for the aggregator is 0.58 €. The power exchange is shown in figure 4.9.

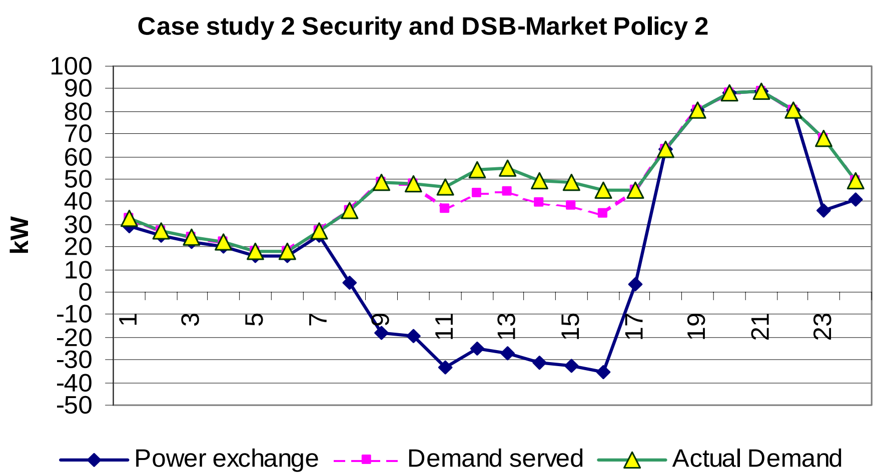


Fig 4.9 *Case study 2 security and DSB with Market Policy 2*.

4.7 Results from market Policy 1 and load Option B when steady state security constraints are concerned.

If steady state security is taken into account and the loads are paid in order to be shed in case of emergency, the additional cost will be (6.8Ect/kWh*104kWh)=7.07 € higher, reaching 170.82€. The latter is 2.74% lower than the solution without DSB. The following table summarizes the results from Case study 1 with security constraints.

Case study 2

For case study 2 the corresponding cost will be (6.8Ect/kWh60*kWh)= 4.08 € higher, reaching 67.21€..

4.8 Conclusions

The following tables summarize the results with security constraints from both Case studies.

Table 4.9 Summarizing costs for DSB with security constraints for case study 1

	Policy 1–Option A	Policy 1–Option B	Policy 2–Option A	Policy 2 –Option B
Change in Cost /revenues compared to no DSB	-12.26€-6.99%	-4.65€-2.65%	0.24€+12.35%	0€-0%
Change in cost /revenues due to Security constraint	+13.06€+8.7%	+9.61€+5.96%	-9.82€-83.43%	0€ 0%

Table 4.10 Summarizing costs for DSB with security constraints for case study 2

	Policy 1–Option A	Policy 1–Option B	Policy 2–Option A	Policy 2 –Option B
Change in Cost /revenues compared to no DSB	-4.05 €-6.02%	+0.03 € +0.04%	3.61 € +119 %	0€-0%
Change in cost /revenues due to Security constraint	+13.63€+27.54 %	+13.63€ +25.32%	10.64 € -94.83%	0€ 0%

From the analysis performed in this section it can be concluded that adopting DSB options not only help the customers to decrease their energy cost by avoiding excessive charges for “low” priority loads but also may decrease the operating cost for all the end users of the Microgrid.
DSB options have more significant impact when Market Policy 1 is applied because the charge is not the open market price but lower. In such a case not only the customers that their demand is shed reduce their energy operating cost but also the other end users due to the lower operating cost.
DSB for Steady state security not only can decrease the operating cost compared to no DSB case but also provide the “high” priority loads the most desired ones in case of an emergency with higher security indices. The increase in cost is significant as also identified in Section 3.

5.Load Flow Results-Voltages

A program for calculating the voltages at the nodes of the Microgrid has been developed and integrated within the software for Market policy 2. Results from this software are shown in the diagrams below. The power factor is 0.85 lagging for the residential and the commercial consumers and 0.9 for the industrial ones. All calculations have been made at p.u of base Vbase=400V and Sbase=100kVA. The network data are presented in Appendix. It has also been assumed that in the μ-sources the power electronics interface has been adjusted to give or absorb zero reactive power.

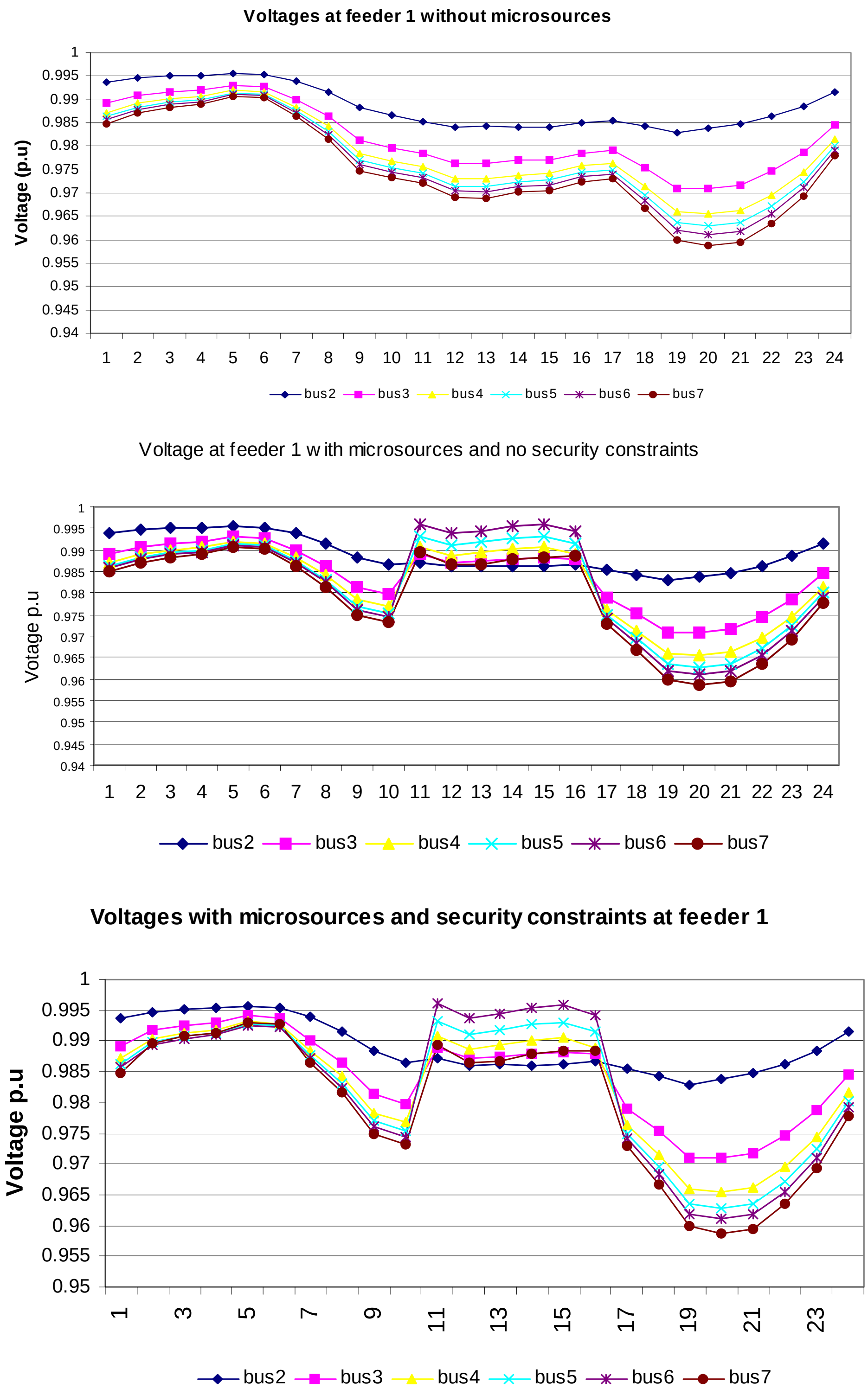


Figure 5.1 *Voltages at feeder 1.*

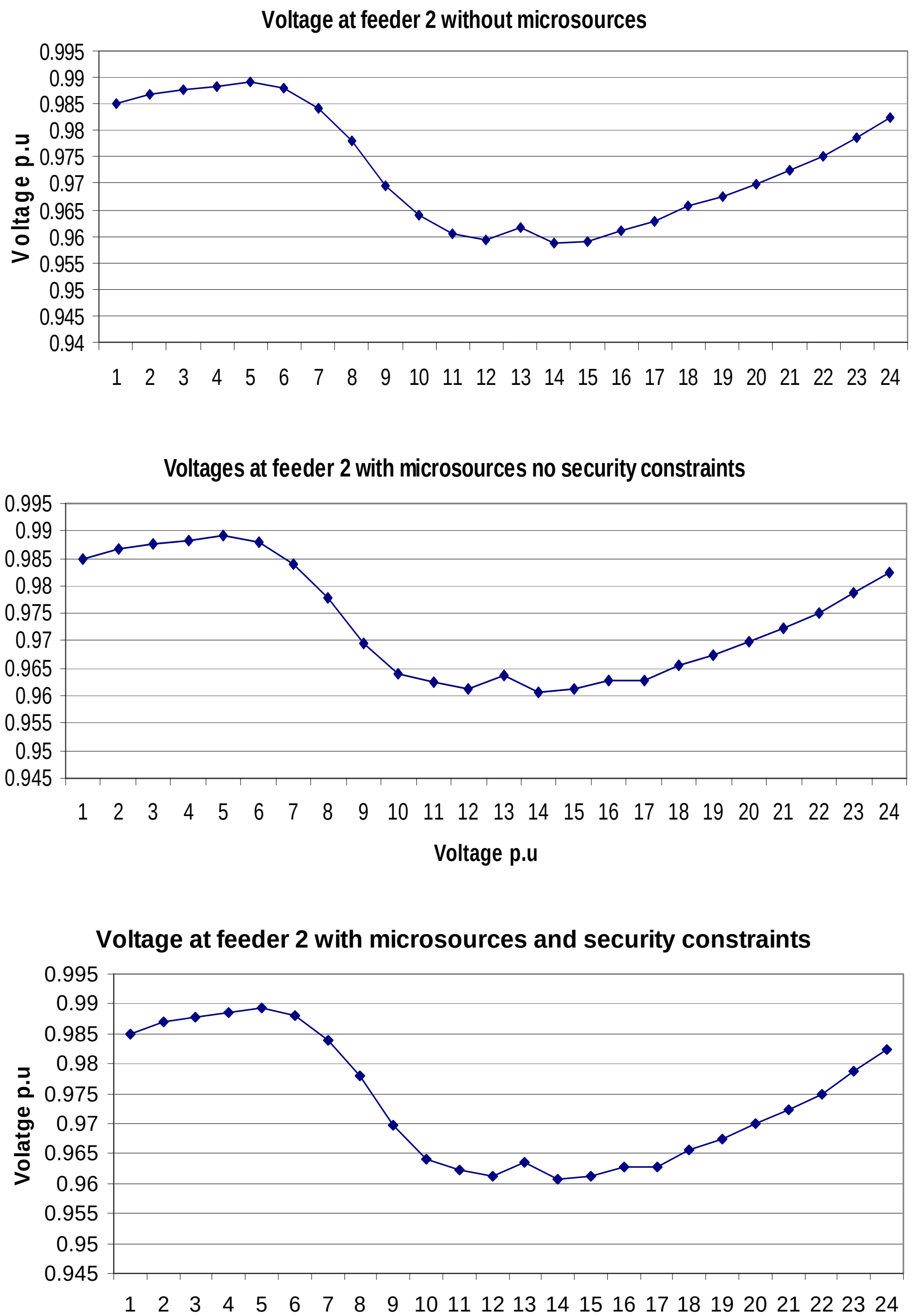


Figure 5.2 *Voltages at feeder 2*

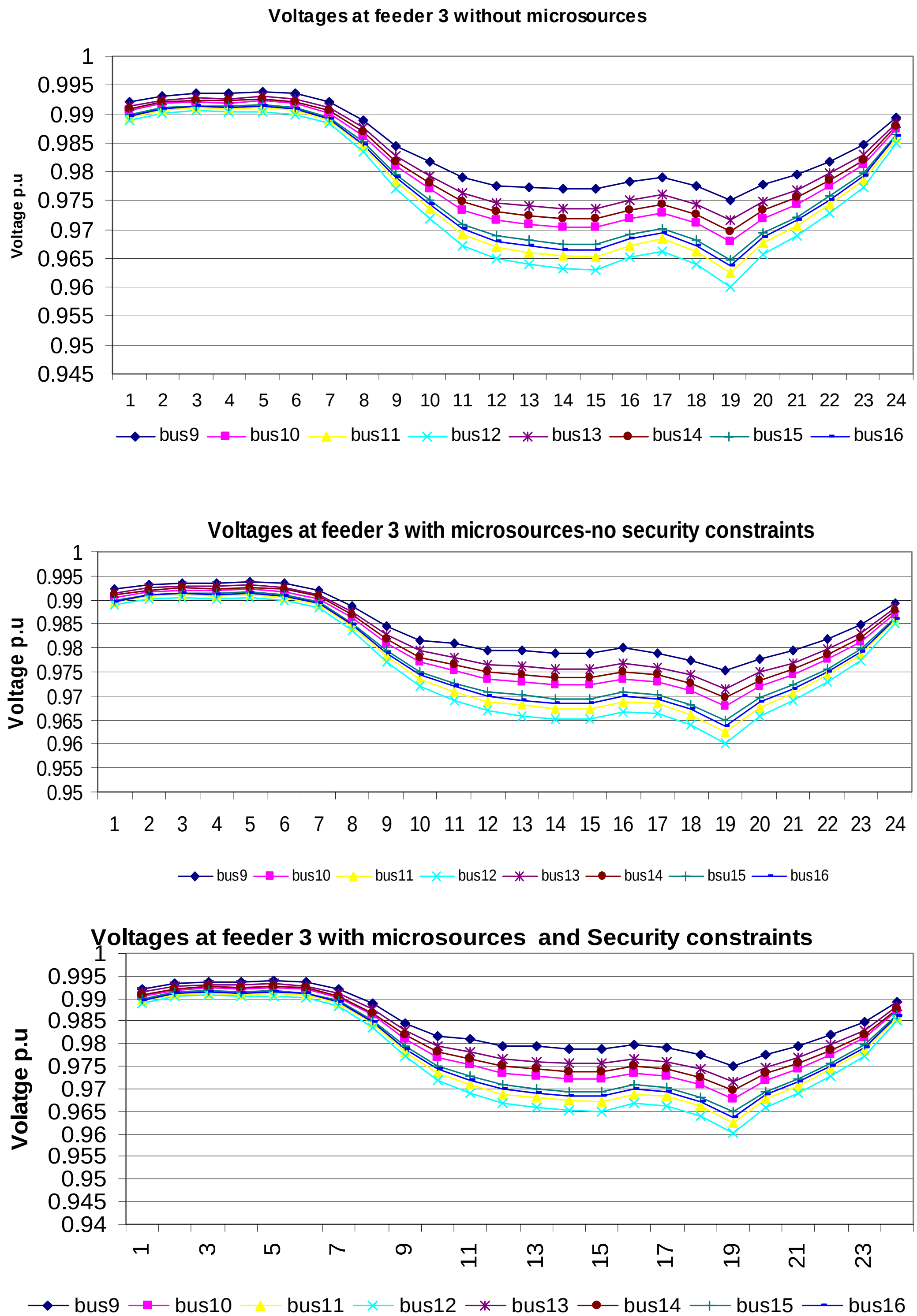


Figure 5.3 *Voltage values at feeder 3.*

From the above figures it can be seen that the voltages at the buses of the feeder with the μ-sources are increased up to 2.5% when the μ-sources are committed and are dispatched at their maximum capacity for that time. The voltages in the other feeders are influenced as well, but to smaller extent, maximum up to 0.2%, since less active power is exchanged with the grid and therefore the voltage drop at the transformer is lower. Using μ-sources production helps so that the voltage drop at node No8,feeder 2 is less than 4%

whereas without the μ-sources this drop exceeds 4%. Minimum voltage value is observed at bus No 7 during the 20th hour being 4.13% below the nominal level.

5.1 Facing violation of voltage limits and influence in the cost

Let us assume that no consumer wishes voltage values below 96% the nominal voltage –4% voltage drop. This violation is experienced during the 20th and the 21st hour at node no7. During that time no μ-source was committed. In order to increase voltage at no 7 at 96%, the active power bought from the main grid should be decreased.:

When the voltages are lower than the acceptable limits then the production of μ-sources should be increased .The maximum value for this decrease is found using the following equation.

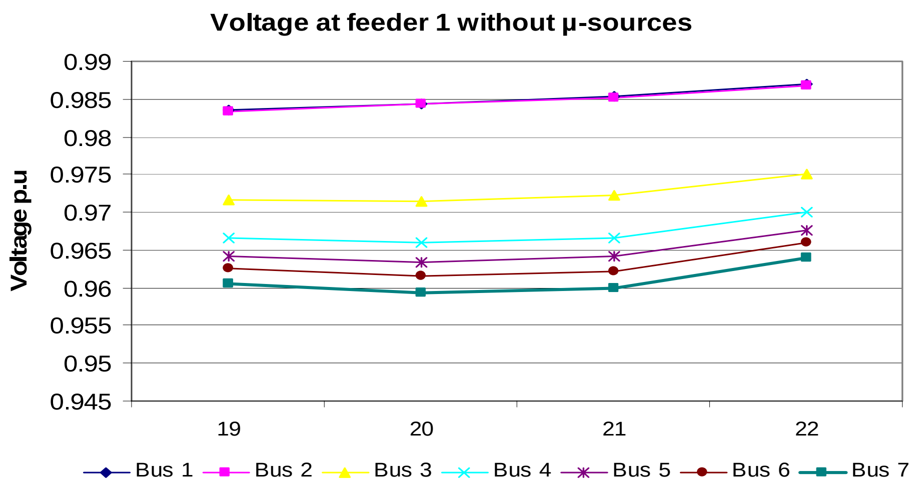
$$RP + XQ = (lowVoltageLimit - \min Voltage) \cdot \min Voltage^2 \qquad (1)$$

Where P, Q are respectively the surplus active and reactive power production needed from the μ-sources and lowVoltagelimit, the acceptable lower limit for the voltage here 0.96. The minimum value of the unacceptable voltage for the MICROGRID is denoted as minVoltage. R and X are the values of the interconnection transformer. All the values are taken in p.u Vbase=400V, Sbase=100kVA.

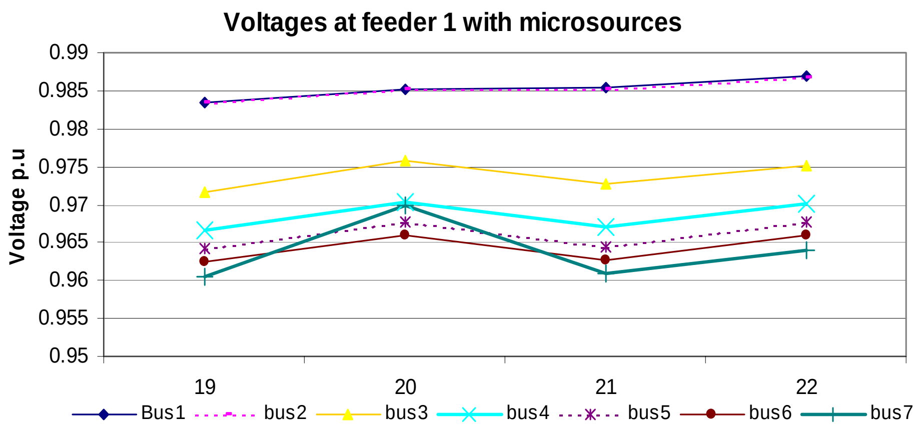
For the time being in order to simplify the problem a solution can be found if we assume that only the active power of the microsources is modified. The modification is defined by the above equation.

The decrease if we take into account only the active power production from the μ-sources should be 26.67kW for the 20th hour and 2.53kW for the 21st hour. During these hours no μ-source was committed, therefore the most inexpensive combination of units should be committed in order to meet the Voltage limit constraint. For both hours the UC decides that only the Microturbine should be committed that happens to be installed at bus no7. The amount of active power production required to increase voltage at the Microgrid is the lower limit for the dispatch of the μ-source. Due to the high bid price of the Microturbine compared to open market prices, the ED decides that limit to be its production as well.

Voltages at the residential feeder and the level of production for these specific hours are shown in the figures below.



a



b

Figure 5.4 *Voltages at the buses of the residential feeder a) with and b) Microsources operation for voltage limit constraint.*

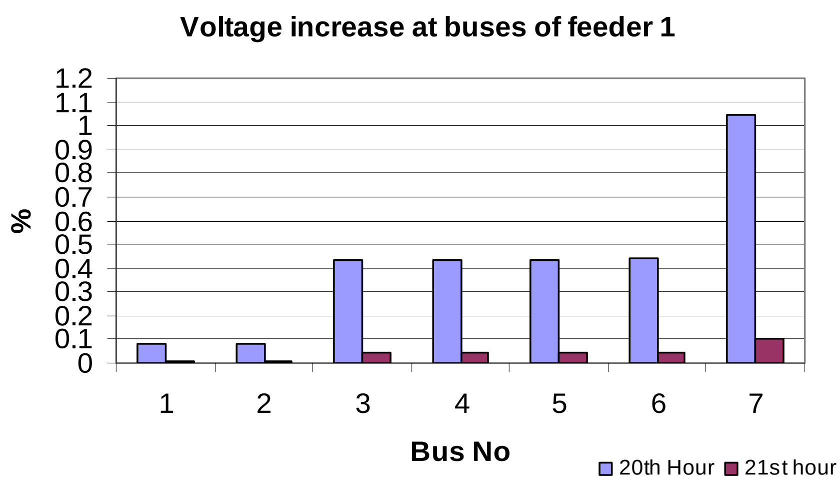


Figure 5.5 *Voltage increase at the buses of the residential feeder*.

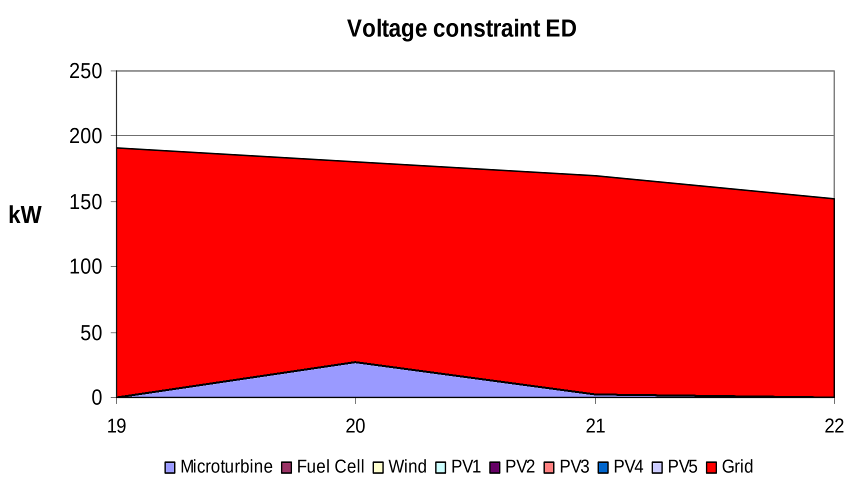


Figure 5.6 *UC and ED Results when Voltage constraints are taken into account*

The voltages are also affected in the buses of the other feeders slightly,0.08% and 0.01 % for these two.
The additional cost due to the Microturbine production will be 1.29 €. Higher .The following table gives the cost that different policies and the adequacy security constraint are shown in the table below.

Table 5.1 Results under voltage violation constraints

	With security Constraints		Without other Security constraints	
Policy	**Policy 1**	**Policy 2**	**Policy 1**	**Policy 2**
Cost(€)	176.55	176.55	166.69	166.69
Energy Cost (€ct/Kwh)	5.71	5.71	5.39	5.39
Cost Increase (%)	0.74	0.74	0.78	0.78

Especially for policy 2 the Aggregator income is reduced by 1.29 € due to the voltage limit constraint.

5.2 Conclusions

As expected DG operation can improve the voltage profile in the Microgrid Nodes especially at the feeder where DG sources are installed. If it is necessary to improve the voltage profile within the Microgrid, DG sources can operate in order to increase the voltages but this may lead in increase in the operating cost since the bids of the necessary Micro sources may be higher than the open market prices. Therefore the installation of DG sources seem to be a solution in improving the voltage profile within a Microgrid during times of low voltages.

6.Environmental benefits.

In order to evaluate the potential environmental benefits from the MICROGRIDS, data about the emissions from the main grid and data about the emissions of the μ-sources should be taken into account. The emissions for which calculations are made are : CO_2 , SO_2, NO_X and Particulate Matter

6.1 Emissions of the main grid

The production of the microsources displaces power from the main grid. Thus the emissions avoided is an average value of the main grid emissions multiplied by the production of the microsources. In our study typical values of emissions from the Greek Interconnected System have been used, as it is stated in the table below. For demand 3079 kWh for the Microgrid the expected emissions without any μ-source installed is also given in table 6.1

Table 6.1 Emissions from Greek Interconnected system

Pollutants	gr/kWh	Emissions (kg)
CO_2	889	2737
SO_2	1.8	5.53
NO_X	1.6	4.96
Particulate Matter	0.501	1.54

6.2 Impact of Microsources

From the microsources installed the ones that consume fuels have emissions that are significantly lower than the ones in the main grid. Whereas the Renewable such as wind solar energy have zero emission in their operation. It is assumed that the fuel burned by the Microturbines and the Fuel Cells is Natural gas. The following table give the data used for our analysis :

Table 6.2 Typical emission data for Micro-sources

UnitName	**CO2_coeff (gr/kWh)**	**NOX_coeff (gr/kwh)**	**SO2_coeff (gr/kWh)**	**Particulate Matter (gr/kWh)**
Microturbine	724.6	0.2	0.004	0.041
FuelCell	489	0.01	0.003	0.001
Wind1	0	0	0	0
PV1	0	0	0	0
PV2	0	0	0	0
PV3	0	0	0	0
PV4	0	0	0	0
PV5	0	0	0	0

These data are Available on line
http://www.epa.gov/globalwarming/greenhouse/greenhouse18/distributed.html
Emissions data from Joel Bluestein, Energy and Environmental Analysis, Inc. The emissions data for the gas-fired engine assume a rich-burn engine with a three-way catalyst.

6.2.1 Changes in cost and emissions avoided.

a) If we assume that all the μ-sources were committed so that the CO_2 emissions are minimized , then the emissions avoided would have been :

548 kg CO_2	20% reduction
2.36kgr NO_X.	42.6% reduction
2.812 kgr SO_2	56.7% reduction
Particulate Matter 756 g	50% reduction

The cost for the whole period would be 216.34 € compared to 177.17 € of the solution without having any μ-sources committed reaching 22.11% higher cost .The above emission levels are the lowest for the specific Microgrid.

b)Compared to committing μ-sources according to market policy 1 or 2 the cost is higher by 30.4% but the emissions avoided would have been :

148 kg CO_2	5.41%
736 g NO_X	13.29%
620 gr SO_2	12.5%
Particulate Matter 196 g	12.73%

Therefore the CO_2 emissions avoided are reduced by 73% .
c)If it is assumed that the Microsources are committed according to their CO_2emissions level but they are dispatched according to their bids then the cost would have been 204.95 € -5.26% lower than the case of optimum environmental scheduling. But the emissions would have been :

368 kg CO_2	13.45% reduction
1940 g NO_X	35.02% reduction
1640 gr SO_2	33.06% reduction
Particulate Matter 524 g	34.03% reduction

The emissions avoided however would have been 32.84% lower than in the optimum case.
The financial results and the CO_2 emissions avoided are summarized in the following table.

Table 6.3 Summarizing financial results and CO_2 emissions avoided

	Change in cost compared to grid only operation	Reduction in CO_2 emissions avoided compared to optimum environmental operation
Grid Only	0	100%
MGCC market policy 1	-6.6%	73%
Unit Commitment and Economic Dispatch based on environmental criteria	+22.11%	0%
Unit Commitment based on environmental criteria and Economic Dispatch based on financial criteria	+15.68%	32.84%

The results from the emissions avoided can be viewed in the MGCC Screen as follows

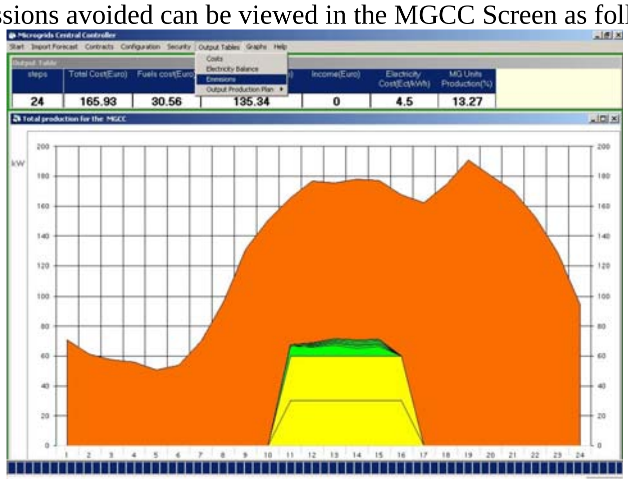


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Figure 6.1 *The main Screen of the software where the user can access the Emissions screen*

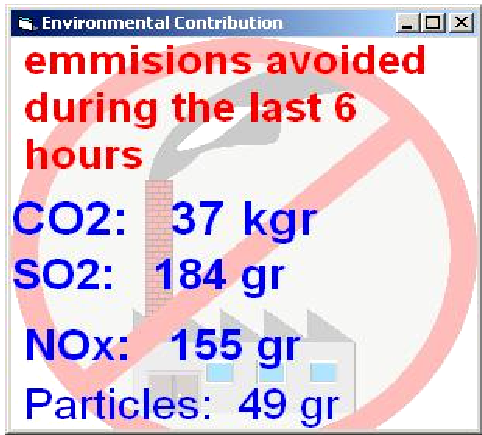

Figure 6.2 *The emissions avoided because of the MICROGRID proposed operation*

Table 6.4 Policy 2 and environmental results

With security		Without security	
153 kg CO_2	5.6%	146kg CO_2	5.33%
758 gr NO_X	13.68%	700 gr NO_X	12.64%
711 gr SO_2	14.33%	655 gr SO_2	13.21%
Particulate Matter 214 g	13.9%	Particulate Matter 198 g	12.86%

6.3 Conclusions

According to the analysis in the previous sections it can be concluded that committing DG sources is not only financially beneficial but also environmentally. The reduction in NO_X, SO_2 and particulate matter is greater in percentage than CO2 reduction due to the fact that the fuel burning units use Natural Gas that has lower emission levels in particulate Matter, and SO2 compared to thermal stations that use Lignite or Heavy oil. The strictly environmental operation of the Microgrid leads to increase of the operating cost as Table 6.3 implies since during low demand periods, high values of bids are accepted to comply with such a constraint. Therefore for such an operation the customers should agree that the operating cost will be increased in order to increase the environmental impact of Microgrids.

7.Analysis of RES scenarios – Participation in competitive market

The scope of this analysis is to evaluate the impact of RES in a Microgrid in competitive markets. In previous sections feed-in tariffs for RES have been used while the owners of the fuel consuming units were interested in meeting the operating cost of their units. In this section bidding values for μ-sources take into account not only their operating cost but also the pay-back period with or without any subsidy.
Different prices from ApX, more volatile than the ones used in the previous sections have been used (8th October 2003). The load consumption is assumed the same as in the previous sections as well as the RES forecast used. The analysis has been performed for the first case study network with all the feeders of the case study network. Similar analysis can be made for the case study network with one feeder only. In general for 2003 prices were rather volatile since for more than 103 hours , the prices exceeded 400€/MWh.

Table 7.1 Prices From ApX On The 8TH October 2003

Hour	Price €/MWh	Hour	Price €/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

During this day the cost without m-sources is 471.83 €.
For the RES based DG the annual cost is distributed 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 [1].
Both Micro-Turbine and Fuel Cell are assumed to run on natural gas with efficiency 8.8 kWh/m^3 and the fuel price is assumed 10 €ct/ m^3 [2]. For the Micro-Turbine the efficiency is assumed 26% for burning natural gas, while the efficiency of a Fuel Cell is assumed to be 40% [3]. Data from [1], [3] and [4] have been used to calculate the lifetime of the DG sources and the installation costs (July 2004). Depreciation times and installation costs are summarized in Table 7.2. In all cases the interest rate is assumed 8%. The annual cost for each DG unit has been calculated from (7.1)

Table 7.2 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

$$Ann\_Cost = \frac{i\,(1+i)^n}{(1+i)^n - 1} \cdot InsCost \qquad (7.1)$$

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.

7.1 No subsidy for RES

According to the above analysis and if there is no subsidy then the DG bids will be :

Table 7.3 DG bids used

Unit Type	b_i- (€ct/kWh)	c_i (€ct/h)
MT	4.37	85.06
FC	2.84	255.18
WT	10.63	0
PV1	54.84	0
PV2	54.84	0
PV3	54.84	0
PV4	54.84	0
PV5	54.84	0

Case 1. **RES participate in the Microgrid Market as other µ-sources.**

Then the operating cost according to the bids is 370.09€ –21% lower than the no µ-sources case. In such a case the electricity balance is :

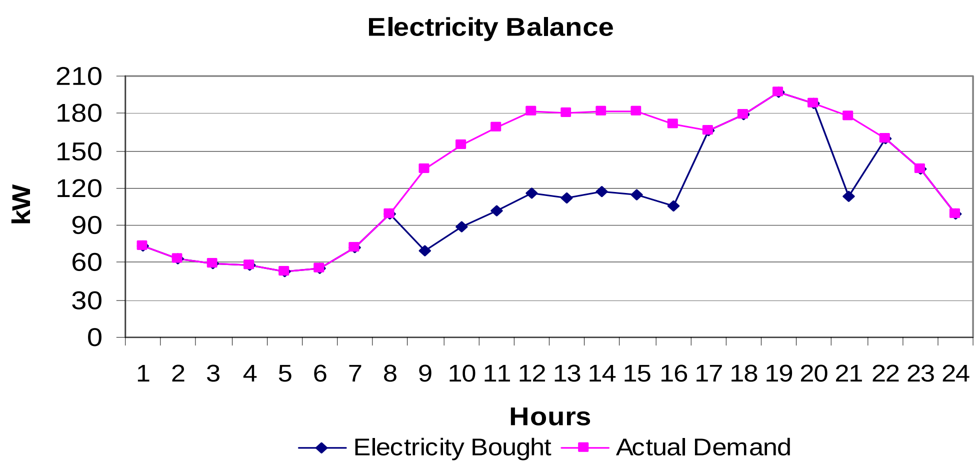

Fig 7.1 *Electricity Balance when RES units participate equally in the Microgrid Market.*

And the production of RES units is given by the following diagram

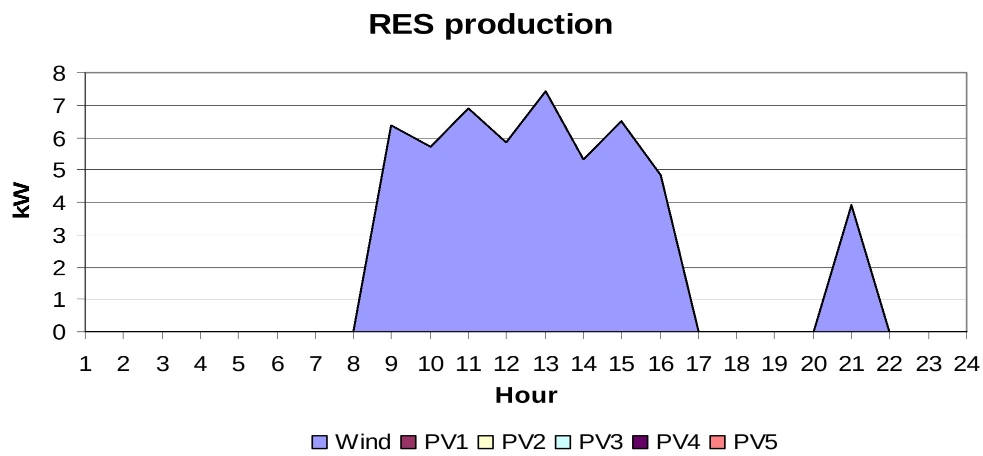

Fig 7.2 *Production of RES units when they participate equally in the Microgrid Market***.**

It can be seen that only Wind Turbine is financially beneficial to operate according to these bids.

Case 2 RES production is always bought within the Microgrids

In this case the MGCC uses always the RES production and then accepts bids from the fuel consuming units and the Grid in order to optimize the Microgrid operation. This is a common practice in many countries, as in Greece, where RES production is always bought from the Market/System Operator.
The production of RES for the specific day is 166.457 kWh, according to the wind and solar data used as the following diagram depicts.

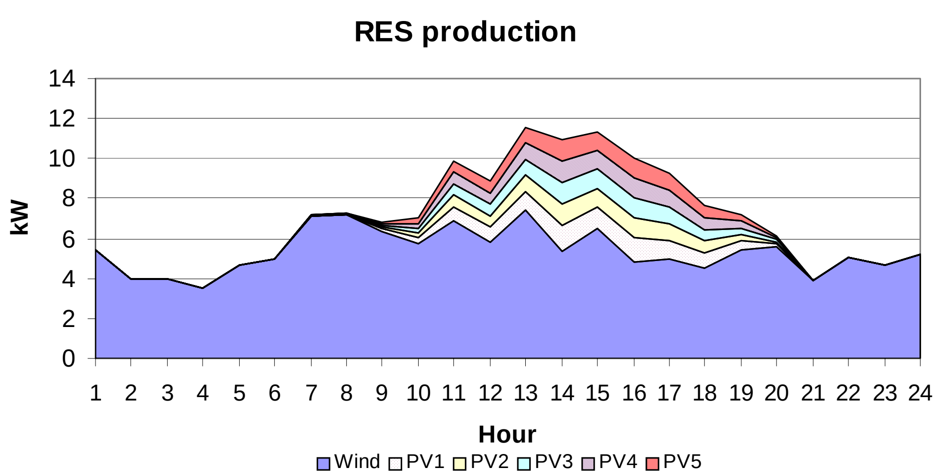

Fig 7.3 *Production of RES units when they participate equally in the Microgrid Market.*

1. RES production is not charged but the cost reduction is distributed to RES owners.
If the RES production is not charged but the whole production of RES is sold within the Microgrid, the operating cost is 353.83€. The cost reduction is 118€ or 25% compared to operation without μ-sources. If the cost reduction is distributed to the owners of the RES then .the value of RES production is 71 €ct/kWh
If the fuel consuming units ,MT and FC were not available the operating cost would be 446.85 €, leading in 24.98 € or 5.29% cost reduction. If the cost reduction is distributed to the owners of the RES then .the value of RES production is 15 €ct/kWh.

2.If the RES units are charged according to their bids, the operating cost will be 388 € or 17.77 % lower than the operating cost without μ-sources but 9.65% higher than the case of not committing the RES units. If the RES units are always committed and the fuel consuming units are not available then the operating cost is 481.07€ increased by 1.96%.

7.2 Subsidy for the installation cost of Wind Turbines and PVs

For the promotion of RES installations Greece, the program "Competitiveness" ,within the 3rd Community Operational Framework Program, offers subsidies for companies willing to install RES. The subsidies are 40% for installing Wind Turbines and 50% for installing PV units.[5]
Taking into account this subsidy scheme the bids of table 7.3 are accordingly modified for RES units.
The new bids for this case are shown in the table 7.4.

Table 7.4 DG bids used

Unit Type	b_i- (€ct/kWh)	c_i (€ct/h)
MT	4.37	85.06
FC	2.84	255.18
WT	6.38	0
PV1	27.42	0
PV2	27.42	0
PV3	27.42	0
PV4	27.42	0
PV5	27.42	0

Case 1. RES are committed as other μ-sources
Then the operating cost according to the bids is 366.22€ –22.38% lower than the no μ-sources case. In such a case the electricity balance will be :

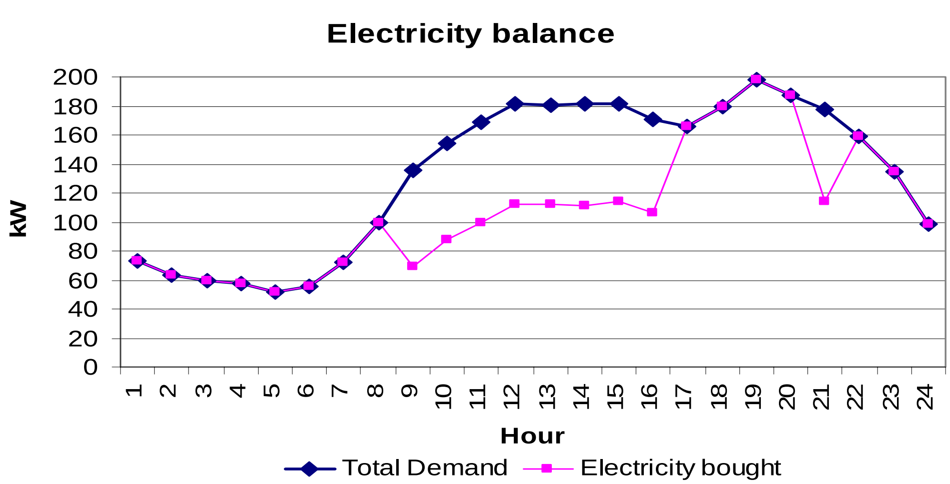

Fig 7.4 *Production of RES units when they participate equally in the Microgrid Market.*

And the production of RES units is given by the following diagram

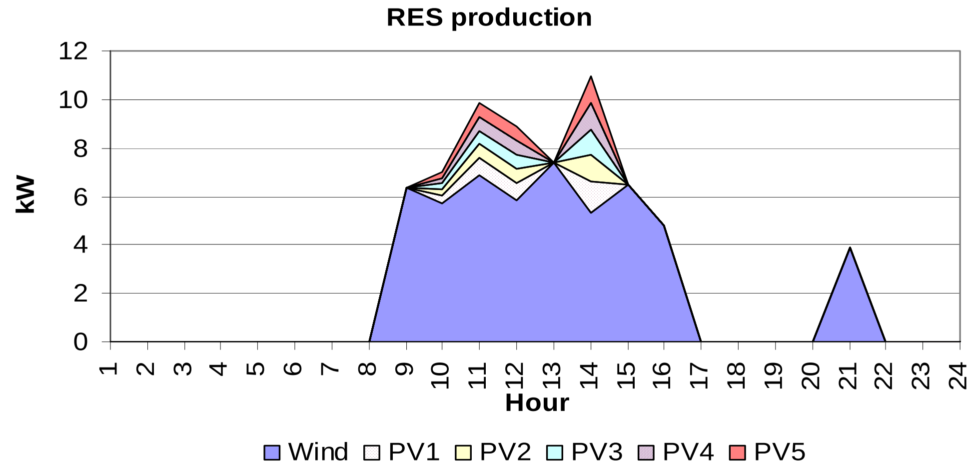

Fig 7.5 *Production of RES units when they participate equally in the Microgrid Market.*

In such a case the PV bids are accepted for a few hours since they are lower than the case of no subsidy.

Case 2 RES production is always bought within the Microgrids

1.RES production is not charged but the cost reduction is distributed to RES owners.
If the RES production is not charged but the whole production of RES is sold within the Microgrid, then the operating cost is 353.83€.
If the fuel consuming units ,MT and FC were not available the operating cost would be 446.85 €, leading in 24.98 € or 5.29% cost reduction.

2.If the RES units are charged according to their bids then the operating cost is 372.33 €. –21.09 % lower than the operating cost without μ-sources but 1.67% higher than the case of not committing the RES units.
If the RES units are always committed and the fuel consuming units are not available then the operating cost is 466.01€ or 1.96% lower than the cost without μ-sources.

7.3 Conclusions

The following tables summarize the results from the above analysis The bids found in the Appendix were used for the case of feed-in tariffs in order to compare the results with the other policies for RES.

Table 7.5 RES always committed

	All μ-sources available		Fuel consuming units not available	
Subsidy Policy	Cost	Cost Reduction compared to no μ-sources	Cost	Reduction compared to no μ-sources
Free- Distribution of revenues to RES owners	353.83 € -(71€/kWh)	25%	446.85 €	5.29%
Without subsidy	388 €	17.77%	481.07 €	1.96% (increase)
With subsidy	373.23 €	20.9%	466.01 €	1.23%
Under feed-in Tariff	366.82 €	22.26%	459.84 €	2.54%

Table 7.6 RES committed as other μ-sources.

Subsidy policy	Cost	Reduction compared to no μ-sources
Without subsidy	370.09 €	21.56%
With subsidy	366.22€	22.38%
Under feed-in Tariff	362.91€	23.08%

Comparing results from this section and previous sections it can be concluded that Microgrid can have a much higher impact in cost reduction when the prices are higher. Installing RES in a Microgrid can be beneficial especially in days with high prices even if they operate, during hours that their operation is not beneficial The impact of fuel consuming units is also significant since buying active power from the grid during periods with high costs is avoided.

Subsidy does not only help in the timely pay-back of RES but also helps in reducing the operating cost of a Microgrid as tables 7.5 and 7.6 indicate.

8. General Conclusions

The analysis in the previous sections can be summarized in the following.

1. Accepting DG bids lead to decrease of the operating cost, that is higher when the DG capacity is high compared to the demand (study case 2)
2. Steady state security constraints help in increasing the autonomy of the study case network but increase the operating cost. The increase in operating cost is higher when the capacity of the network is lower since the DG sources can more often meet the total demand.
3. Demand Side Bidding options help in decreasing the operating cost in Market policy 1 giving the opportunity to end-users to avoid excessive charges for “low” priority loads but also decreasing the operating cost for the other end-users. Furthermore, DSB can help in the fulfillment of steady state security constraints by decreasing the operating cost but most important by providing to “high” priority loads the opportunity to operate for longer time in case of grid disconnection. Therefore the most important appliances for an end-user can still be operative in case of grid disconnection, relieving the impact of such an event
4. Microsources can be used to decrease the voltage drops in a Microgrid especially for the feeders that have been installed in.
5. Microgrids can help in decreasing the emissions, since they operate on high RES penetration and low–emissions unit. However, an operation that is based only on environmental criteria has significantly higher operating cost.
6. Even without any subsidy, there may be periods that RES can be financially beneficial. However , subsidy can help in the timely pay back of the RES investment and the further decrease in the operating cost.

9.Bibliography

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APPENDIX -DATA USED

Hourly values were used for these first iterations of the algorithms
Active power Time-series

Table A1.Data for the units used :

Unit ID	Unit Name	Minimum Capacity (kW)	Maximum Capacity (kW)	Cost Coeff A (ai- Ect/kWh^2)	Cost Coeff B (Ect/Kwh)	Cost Coeff C (Ect/h)	Start Up Cost (Ect)	Start up Time (min)
1	Micro turbine	2	30	0.01	5.16	46.1	5	3
2	FuelCel l	1	30	0.01	3.04	130	5	3
3	Wind1	0.1	15	0.01	7.8	1.1	0	<1
4	PV1	0.05	3	0.01	7.8	1	0	0
5	PV2	0.05	2.5	0.01	7.8	1	0	0
6	PV3	0.05	2.5	0.01	7.8	1	0	0
7	PV4	0.05	2.5	0.01	7.8	0.1	0	0
8	PV5	0.05	2.5	0	7.8	1.2	0	0

The values in cost function are in Eurocents. The values for bi for the Renewable energy sources are the ones that the Independent Power Suppliers with Renewables receive in Greece for selling electricity to the grid. Small values for ai and ci have been used for bias reasons.

The value for the Microturbine and Fuel cells is calculated according to the performance of the units and the value of Natural gas 10Ect/m^3.

Table A2. Line data of the MICROGRID

Sending Bus	Receiving Bus	R(pu)	X(pu)
0	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

The units have been calculated in power base of 100 kVA and voltage base 400V.

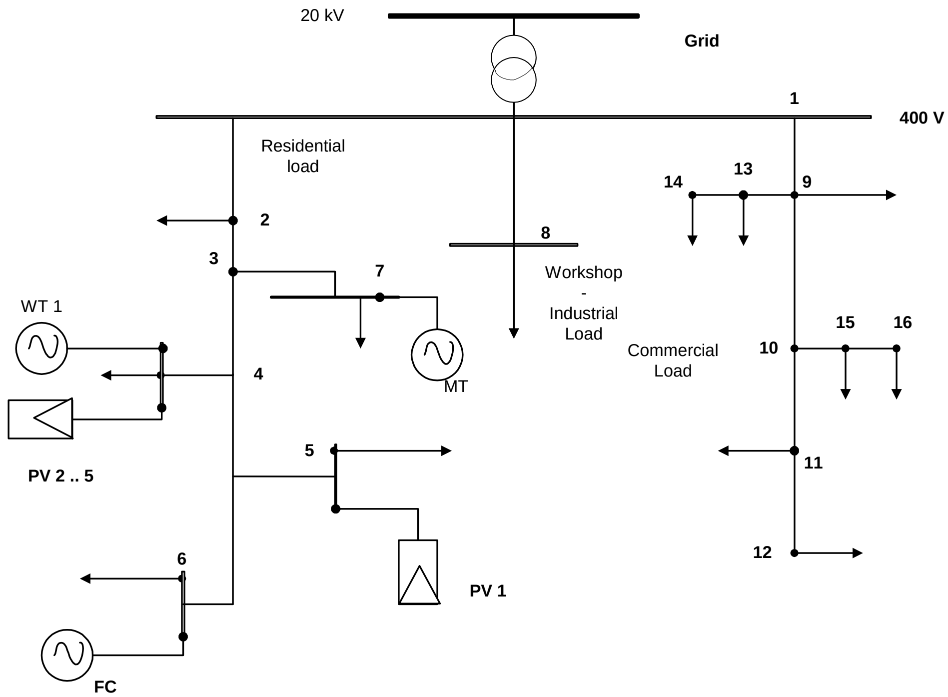

Fig. A1. *The study case network.*

The following data contains the time-series used as output kW/Installed kW. The time-series used come from the power system of the Greek island of Kythnos where PV and wind Turbines have been installed.

Table A2.Renewable power time-series.

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

Table A3. Prices of the 6th October 2003 from Amsterdam Power exchange

Hour	Price(€/MWh)	Hour	Price(€/MWh)
1	24	13	99
2	17.7	14	149
3	13.01	15	99
4	9.69	16	79
5	3	17	40
6	17.01	18	36.47
7	27.1	19	35.85
8	38.64	20	41.3
9	51.69	21	44.48
10	52.6	22	34.8
11	81	23	30
12	100	24	22.5

MICROGRIDS
Contract No: ENK5-CT-2002-00610

LABEIN CONTRIBUTION

Access: Restricted to project members

Contents

Demand Side Management, Case Studies

Introduction

This part of the deliverable is a continuation of the Demand Side Management part on deliverable DC1. On that deliverable the basis of a direct load control system that independently runs a load shifting and a load curtailment algorithm is presented. The objective of both algorithms is to bring the actual load consumption curve within the microgrid or a part of the microgrid as close as possible to an objective load curve. The algorithms have knowledge of the control possibilities that have been agreed by the MGCC and each customer, and schedule control orders over particular appliance types.

The impact of the developed shifting algorithm depends heavily on several variables:

Shape and nature of the objective curve: The objective curve can be built having in mind different considerations. It can be built having in mind just minimal cost considerations, in which case it will be obtained from next day's forecasted electricity prices. It can also be built having in mind security considerations or with the aim of keeping the microgrid as independent as possible from the main grid. Case studies showing the three possibilities are presented on this deliverable.

Controllable load: Obviously the amount of load and the time of the day at which it is usually connected is a very important factor for the algorithm. The percentage of the total load that can be controlled is very important. The algorithm targets mainly domestic appliances that have clearly marked consumption patterns and therefore the biggest controllable margin will be concentrated at times where the use of them is more extensive.

Control possibilities: The control over loads creates clear disturbances to the customers exposed to those control actions. The idea explained on deliverable DC1 is that the control actions are taken fulfilling certain conditions agreed between the MGCC and each customer. The wider the control margin agreed, the better for the algorithm.

Control period: The shifting algorithm works over a finite control period, that is usually set to 24 hours. Due to the fact that load consumption is significantly lower at night time than at day time, it is important to have the night hours at the end of the control period. In this way the algorithm has the possibility to move load from peak times to valley hours.

In order to evaluate the impact of each of the previous factors, several case studies will be defined and simulations performed.

1.1. Load Shifting

All the case studies will be based on a base case that is presented next:

1.1.1. Base Case

The DSM system is installed on a microgrid central controller that controls 1100 domestic customers. All these 1100 domestic customers have direct two way communication possibility with the MGCC. For the base case real Spanish power system data from the 6th of October 2003 is used. The control period is defined from 00AM to 24AM, and the time steps are considered to be one hour long. The forecasted load consumption curve of the group of 1100 customers is presented below:

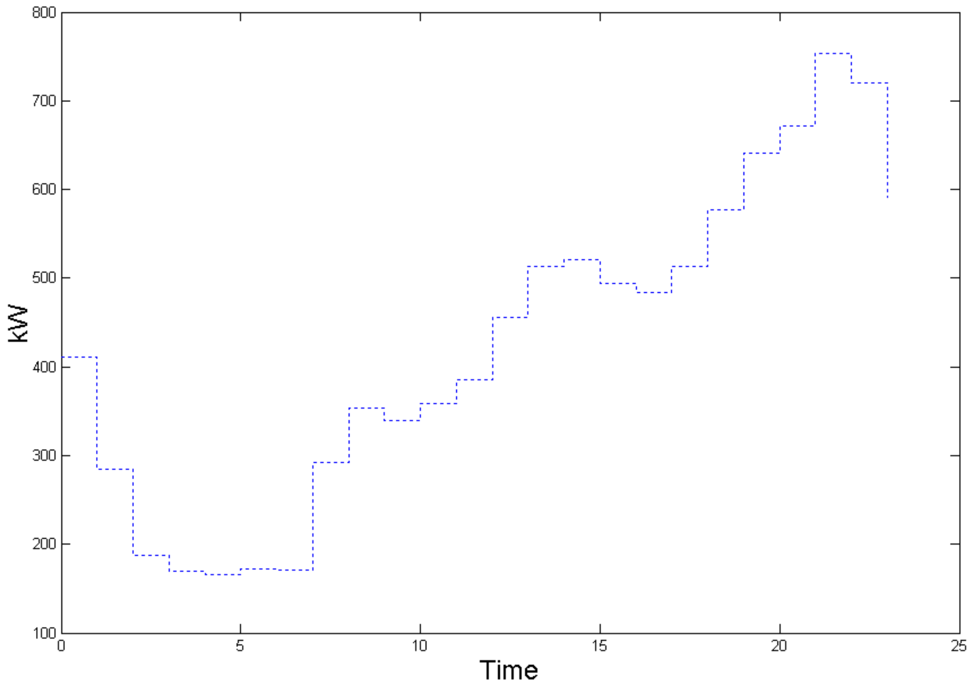

Figure 1.1

Controllable load

On the base case three types of shiftable appliances are considered: washing-machines, dryers and dish-washers. Diversified load consumption curves of the three appliance types are obtained from the INDEL project. Data and curves provided on that project are referred to the year 1997 and need to be actualised to the year 2003. This is carried out applying statistical data provided by the Spanish Government that gives a nation wide overview of the penetration growth that each appliance has experimented during those 6 years. Figure 1.2 shows the diversified curves of each appliance type for 1100 customers if the update is done:

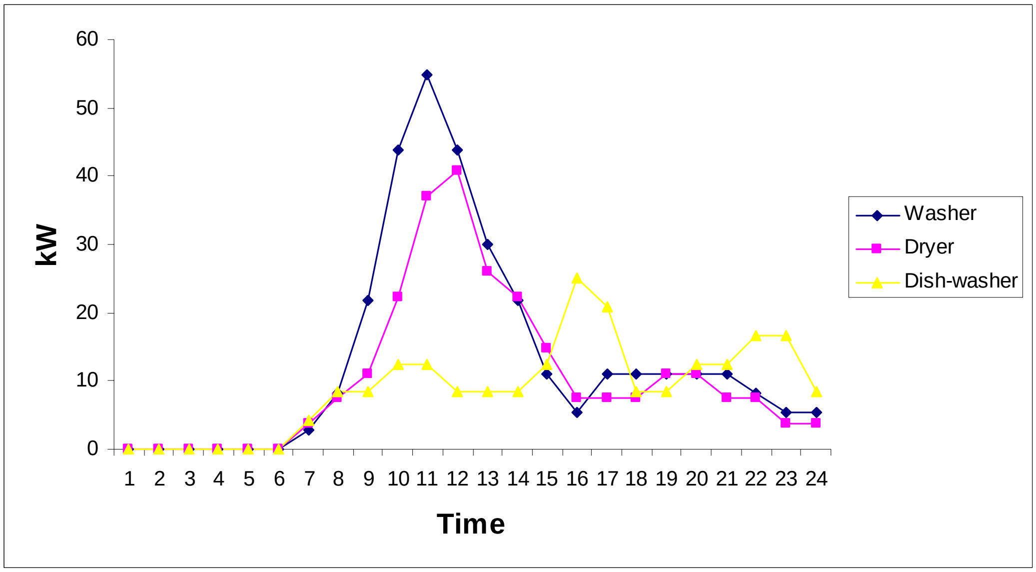

Figure 1.2

Dissagregation

The input that we get from the MGCC are the diversified load consumption curves of different device types, but what the shifting algorithm really needs is the number of devices from each group that are expected to start their consumption at each time step of the given control period. This section explains how to obtain them from the diversified curves.

We will consider that the appliances within each diversified curve are all of the same type: all have the same load consumption pattern and can be controlled in exactly the same way. The general problem formulation for this case is the following:

Calculation of the number of devices starting their consumption at each time step of a given control period from a diversified load consumption curve where all the devices are exactly the same.

The inputs to the problem are:

- Length of the time steps
- Control period (number of time steps): q
- Discreet model of the device load consumption pattern:
    - Duration of it (number of time steps): i
    - Consumption at each time step: p_w for w=1,2,3…i
- Diversified load consumption curve. A power value for each time step: C_n for n=1,2,3…q
- Curve uncertainty

Let us define D_n the number of devices starting their consumption at time step n. They are the q unknowns.
The power C_n at time step n is composed by the consumption of the devices starting their consumption at n and the consumption of the devices that have started their consumption on the previous time steps:

$$C_n = \sum_{w=1}^{i} D_{n-(w-1)} \cdot p_w \qquad (1.1)$$

There is an equation like eq. 1.1 for each time step. We will have a set of q linear equations and q unknowns. The solution to the resulting linear system, eq. 1.2, is unique and straightforward.

$$[A]_{q\times q} \cdot \begin{bmatrix} D_1 \\ D_2 \\ \ldots \\ D_q \end{bmatrix}_{q\times 1} = \begin{bmatrix} C_1 \\ C_2 \\ \ldots \\ C_q \end{bmatrix}_{q\times 1} \qquad (1.2)$$

If the diversified curve does not start with 0, this formulation has a problem on the first time steps. Equation 1.1 considers that at the beginning of the control period there is not any consumption due to devices that were connected just before the start of the given control period. This supposition is probably untrue and makes the number of device connections at the first time steps artificially high. Different solutions can be found to solve this problem. A possible solution is to consider that the immediately previous control period was very similar to the present control period, and that the number of device connections at the end of the previous control period was equal to the number of device connections at the end of the present control period.

The solution to equation 1.2 are in general real numbers that have to be truncated to the closest integer.
The result obtained is calculated supposing that the diversified curve is perfect, but the reality is that it is not, it has a given uncertainty. In order to take this uncertainty into account the calculated number of devices connecting at each time step has to be reduced. Considering that there are less device connections, the number of controllable devices is reduced and therefore we will be in a safe position.
The figure below represents a block diagram of the dissagregation process:

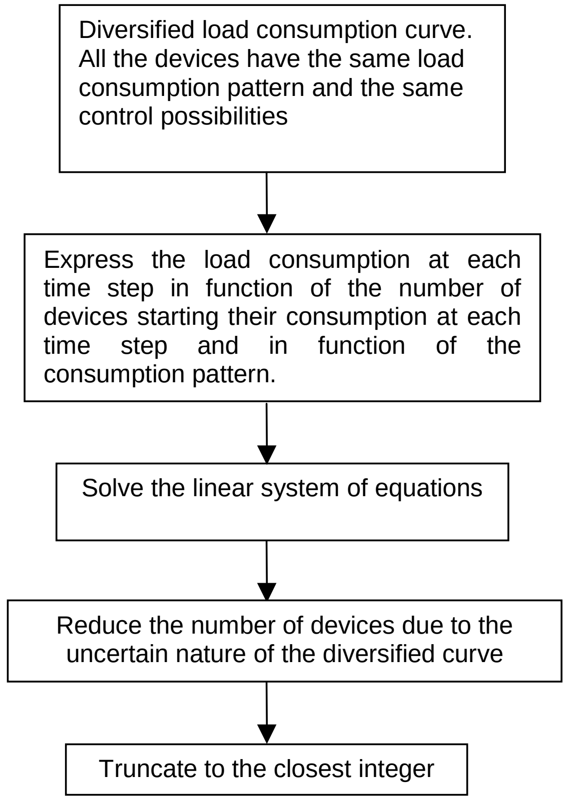

Figure 1.3

On the explained diversified curve dissagregation methodology the statistical uncertainties are taken into consideration reducing the expected number of device connections at each time step. In this way we consider that the possible controllable device connections is smaller and we minimise the possibilities of scheduling load control actions over loads that are not going to be connected.

There is another factor that has not been mentioned yet that introduces further uncertainty. The diversified consumption curves represent the consumption of a set of monitored devices over a given time period. Each device being monitored can be connected more than once during the monitoring period. For example a washing machine can be connected twice per day in some households.
The calculated number of device connections, especially at the end of the day will contain some devices that have already been connected before that day. The control contracts in general allow one single control action per day over each device. In this situation the number of controllable devices has to be further reduced specially at the final time steps of the control period, where the possibility of having second time device connections is bigger.
Obviously a compromise must be found between the security that we will not schedule more control actions than devices will be connected and the amount of controllable load that we can miss.

The load consumption patterns of washing-machines, dryers and dish-washers in this base case are:

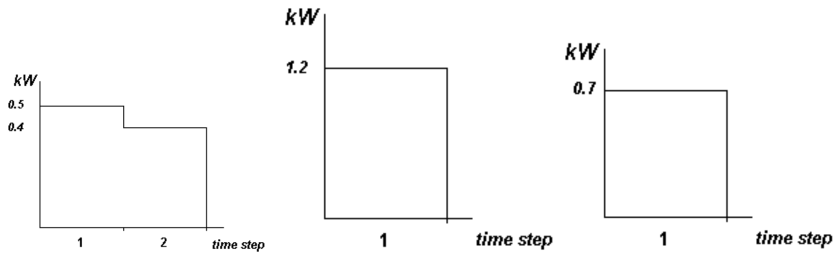

Figure 1.4

If we dissagregate the curves on Figure 1.4 using these patterns and following the explained methodology, the obtained result is:

Time step	Washer connections	Dryer connections	Dish-washers connections
1	0	0	0
2	0	0	0
3	0	0	0
4	0	0	0
5	0	0	0
6	0	0	0
7	5	3	5
8	12	6	11
9	34	9	11
10	60	18	17
11	61	30	17
12	38	33	11
13	29	21	11
14	20	18	11
15	5	12	17
16	6	6	35
17	16	6	29
18	8	6	11
19	15	9	11
20	9	9	17
21	14	6	17
22	5	6	23
23	6	3	23
24	5	3	11
TOTAL	348	204	288

Table 1.1

This provides a load control margin that is presented shadowed on Figure 1.5:

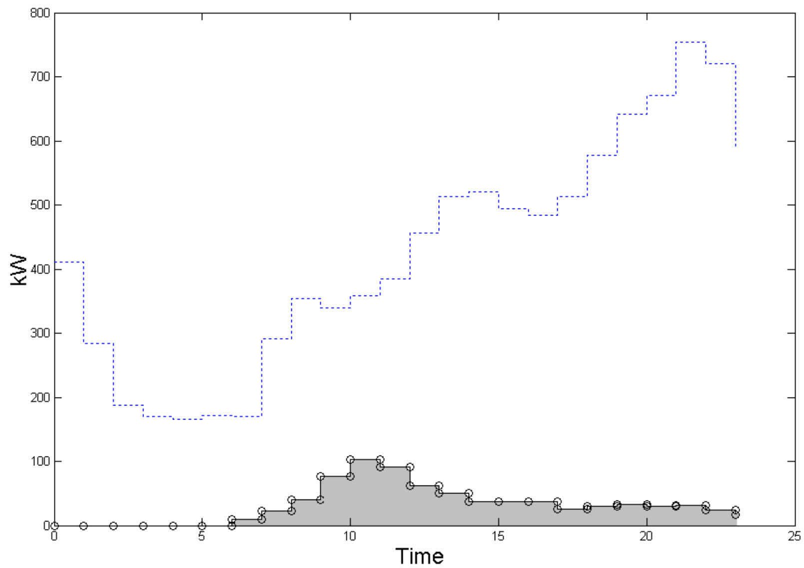

Figure 1.5

1.1.2. Case1

This case study exemplifies the working procedure of the shifting algorithm. In this case the objective curve will be completely based on prices. Figure 1.6 represents the price forecast on the Spanish market for the 6th October 2003.

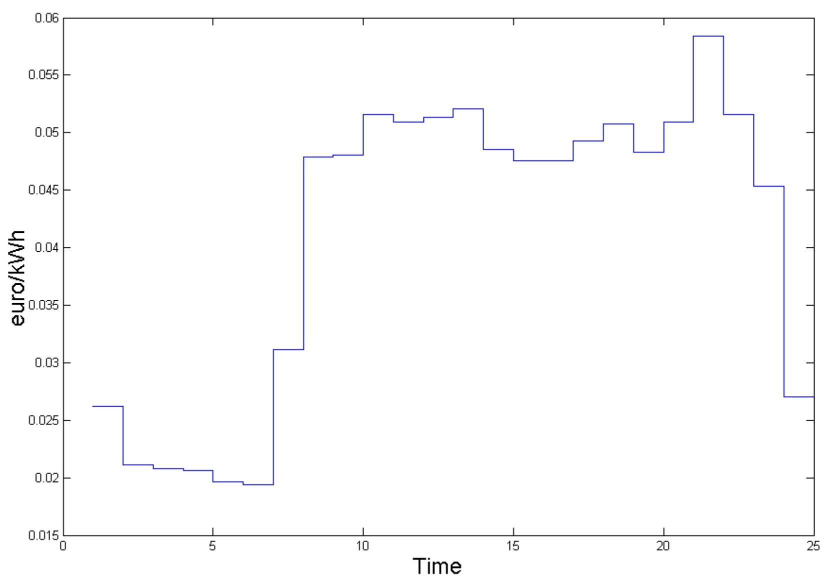

Figure 1.6

The objective curve will then be the inverse of the price curve applied to the total forecasted energy, Figure 1.7:

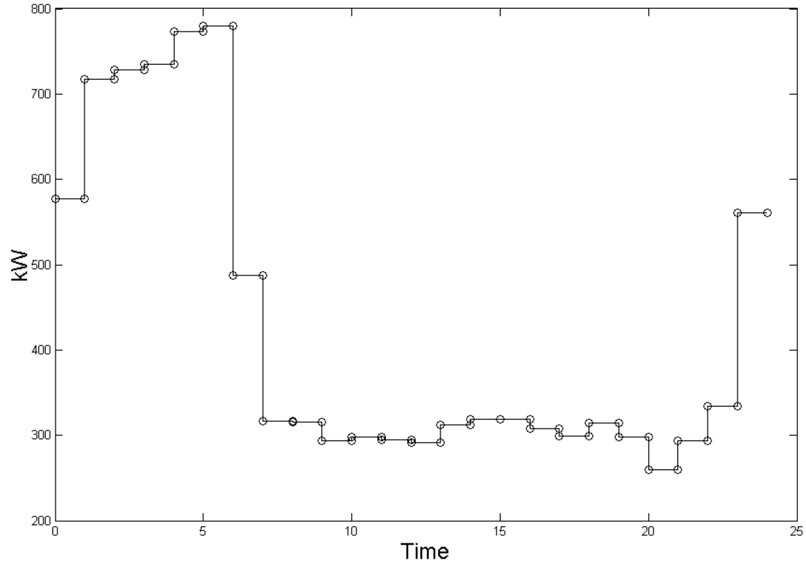

Figure 1.7

To simplify the implementation of the case studies it will be assumed that all the devices have exactly the same control possibility. In this case we assume that all the customers have signed a contract with the MGCC that allows a maximum connection delay of 4 hours for each controllable appliance that they have.

All the previous information is inputted and the shifting algorithm is run providing the following results:

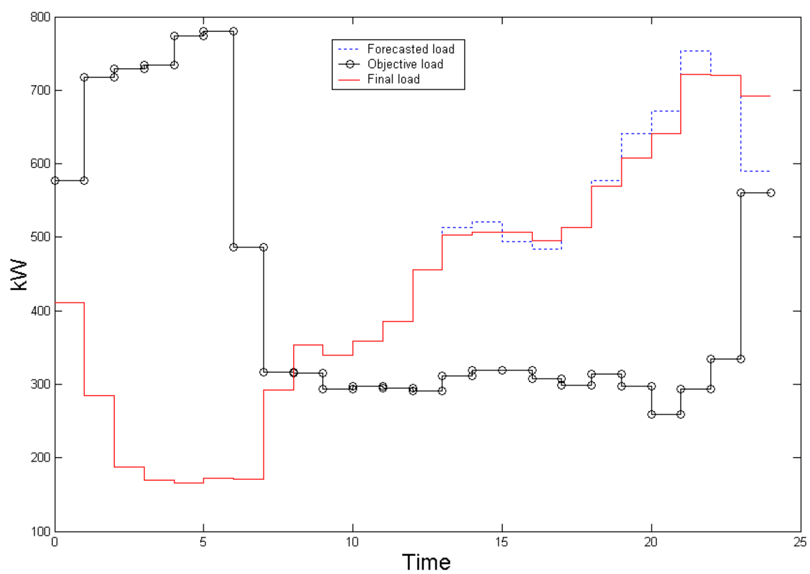

Figure 1.8

It can be seen that the algorithm is almost useless in this case. The algorithm cannot delay much load because the forecasted curve is above the objective curve on the time steps that come after the connection of the majority of the controllable appliances (at the end of the control period).

If we now maintain the same data as on the previous case and change the control period making it from 8:00AM to 8:00AM, the algorithm will certainly be more effective. The new forecasted and objective curves are:

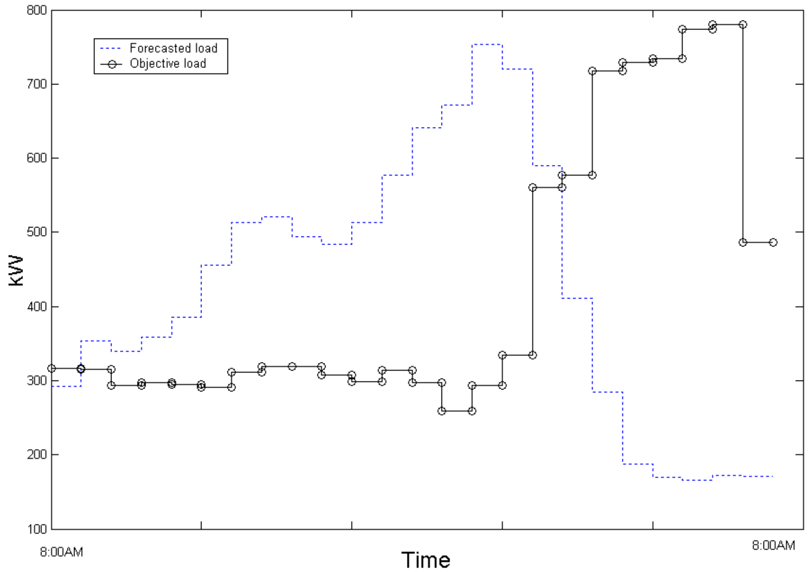

Figure 1.9

Running the shifting algorithm under these conditions the result below is obtained:

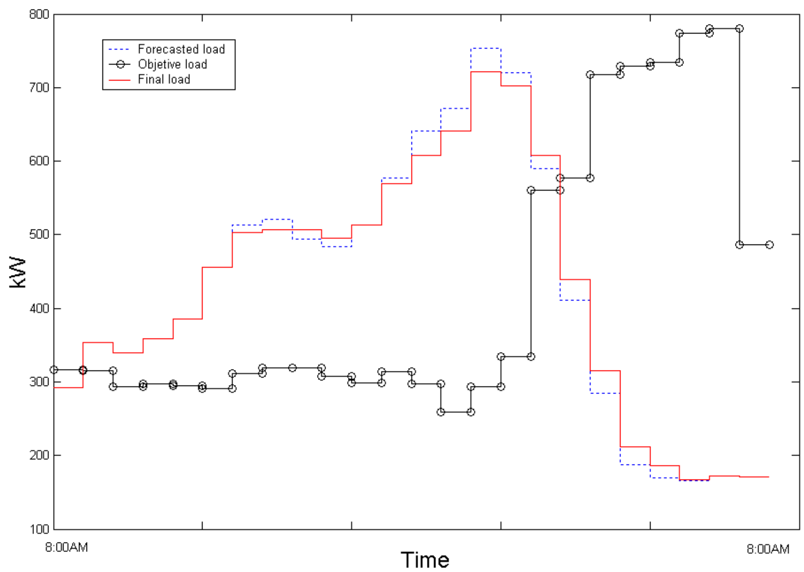

Figure 1.10

It can be seen how some load is moved from expensive time steps to cheap time steps. If we consider that the MGCC has to buy on the market the complete amount of forecasted energy for the given period, we can compare the benefits obtained from the shifting algorithm.

- Cost of energy in the market if no shifting action is applied: 456.6 euros
- Cost of energy in the market if the calculated shifting actions are applied: 453 euro

In both cases the total energy bought is the same. The obtained cost reduction is just a 0.7%. This is because most of the appliances are connected in the morning, at the beginning of the control period, and if they can only be delayed for 4 hours, they cannot be connected at night.

If we now run the shifting algorithm for different maximum allowable delays, we will obtain different final load profiles and different energy costs. The table below contains the results. It has also been considered that in each case the control possibility was exactly the same for all the appliances.

	Energy cost [euros]	Cost reduction %
No control	456.6 euro	0 %
A maximum allowable delay of 4 hours	453 euro	0.7 %
A maximum allowable delay of 8 hours	449 euro	1.5 %
A maximum allowable delay of 12 hours	444 euro	2.6 %
A maximum allowable delay of 24 hours	436 euro	4.3 %

Table 1.2

The table shows that an increase on the control possibilities brings an increase on the obtained cost reduction. This conclusion is logical, the problem is that increasing the allowable control possibilities we also increase the disturbance caused to customers. In this particular case study the obtained cost reduction is small.

In this case the objective curve was completely based on prices and the purpose of the DSM system was to save money. In fuction of the role of the MGCC two cases can arise:

1. The MGCC acts as an aggregator that looks for its own economical interests. It provides the energy to the 1100 customers at a fixed price and then subtracts the contracted compensation, a complete analysis has to be done in order to evaluate if the system is profitable for the MGCC.

2. The MGCC acts as an aggregator that looks for the economical interests of all the customers in the microgrid. In this case the price that customers pay for their electricity is

directly related to the cost of the energy in the market. Customers that allow wider control actions should obtain the biggest benefits.

1.1.3. Case2

Let us now apply the same case study to the Amsterdam Power Exchange market. Figure 1.11 represents the prices on that market on the 6th October 2003. It can be seen that prices are much more variable than on the Spanish market.

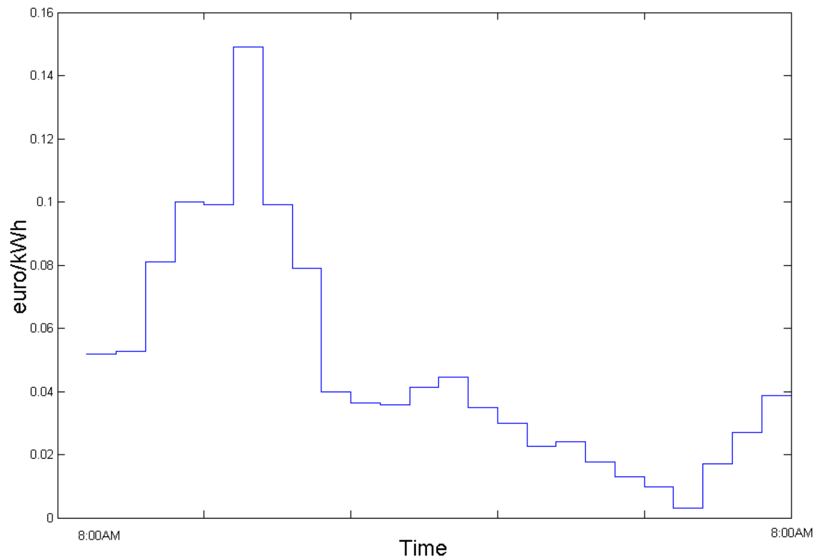

Figure 1.11

This results on the following objective curve:

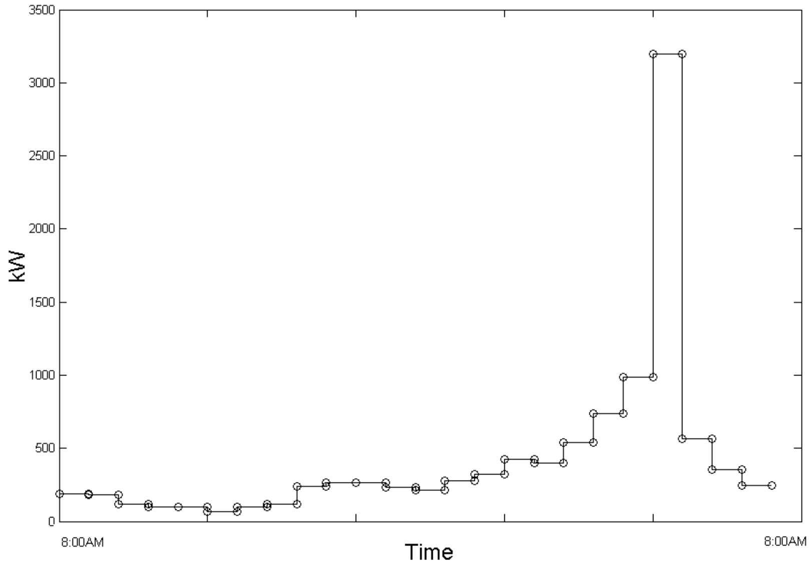

Figure 1.12

If we now run the shifting algorithm under the same conditions of case1 for different maximum allowable delays, we will obtain the following result:

	Energy cost [euros]	Cost reduction %
No control	506.9 euro	0 %
A maximum allowable delay of 4 hours	491.6 euro	3 %
A maximum allowable delay of 8 hours	487 euro	3.7 %
A maximum allowable delay of 12 hours	476 euro	5.9 %
A maximum allowable delay of 24 hours	455 euro	10.07 %

Table 1.3

The graphical result when the maximum allowable delay is 12 hours is presented below:

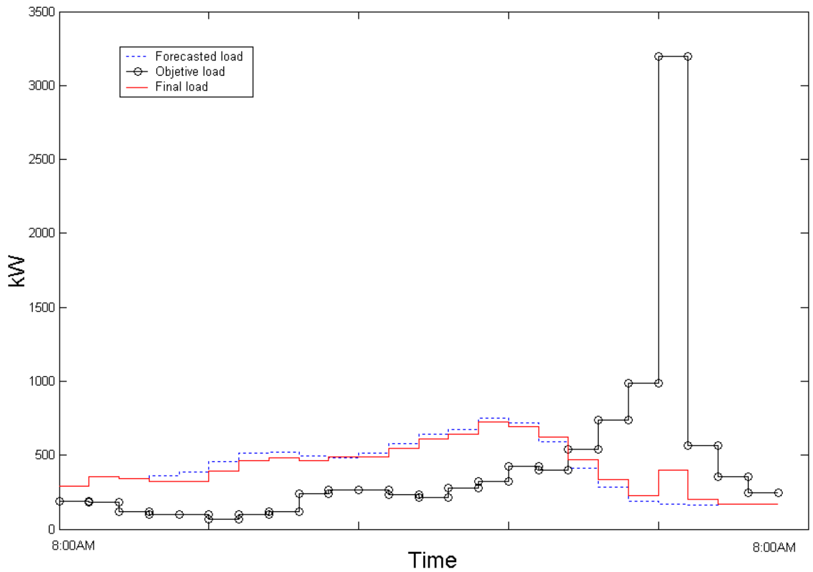

Figure 1.13

The huge price variability makes results much more interesting than the Spanish market case. When the allowable delay is 24 hours the obtained cost reduction is up to 10% even if from the 1100 customers just 348 washers, 204 dryers and 288 dish washers are available for control (Table 1.1). This data comes from the data of the INDEL that has been extrapolated taken into account the total number of domestic customers in the Spanish Power System (22.3 million). The fact is that many of those customers represent empty or holiday houses. If we now consider that from the 1100 customers in our microgrid 525 washers, 305 dryers and 441 dish-washers will be connected (that looks like a more realistic situation), the control margin will be clearly increased. Figure 1.14 shows the new controllable margin:

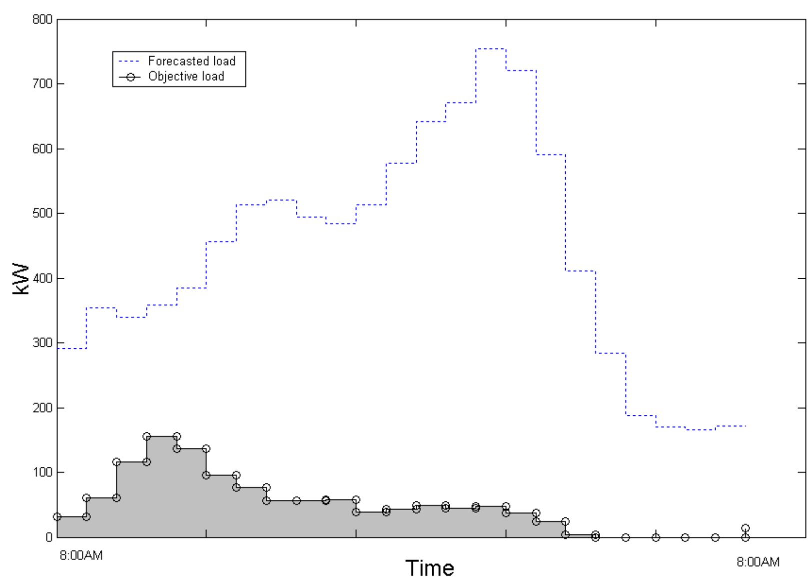

Figure 1.14

Running the same studies as before Table 1.4 is obtained. the cost reduction gets bigger and more interesting in this case, reaching a 15.2% when the control flexibility is total:

	Energy cost [euros]	Cost reduction %
No control	506.9 euro	0 %
A maximum allowable delay of 4 hours	487.4 euro	3.7 %
A maximum allowable delay of 8 hours	477.7 euro	5.7 %
A maximum allowable delay of 12 hours	463.6 euro	8.5 %
A maximum allowable delay of 24 hours	429.4 euro	15.2 %

Table 1.4

The graphical result when the maximum allowable delay is 12 hours is presented below:

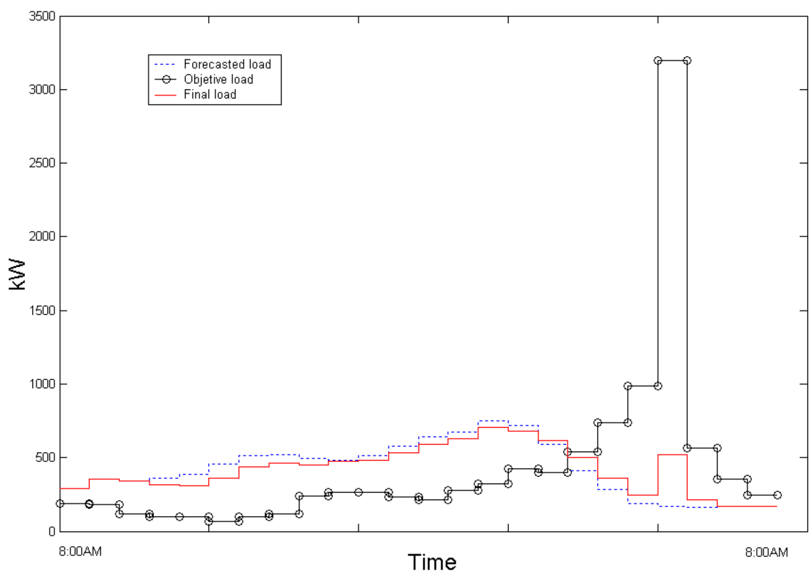

Figure 1.15

The graph shows how the algorithm tries to shift load to the cheapest time step, and this results on a consumption peak at that time step. In this case the resulting peak is build of approximately 250 extra kW and may cause problems to the system making the solution technically infeasible. If that is the case additional technical constraints could be incorporated into the algorithm:

- The final consumption at any time step after the shifting cannot be bigger than the system peak.

- The final consumption at any time step after the shifting cannot be bigger than a certain percent of the non-controlled load at that time step.

1.1.4. Case3

During the previous case studies the parameter that has been used to measure the performance and advantages of the shifting algorithm has been the cost. This approach is not very precise because the algorithm has not been built to minimise cost, the algorithm has been built to bring the load curve as close as possible to an objective load curve. If the objective curve is created having in mind cost concerns, implicitly cost is reduced when the load gets closer to the objective curve.
It might be the case that market prices or energy costs are not the main issue and that we are more concerned about some other aspects of power system operation. In this case we will consider a case where we want to maximise the use of renewable energy resources within the microgrid and minimise the energy traded on the market. Figure 1.16 and Figure 1.17 show the aggregated forecasted output from both the PV plants and the wind generators installed on the microgrid. This particular day the group of photovoltaic plants peak at around 13:00 PM and the wind-farms provide their maximum output at night time.

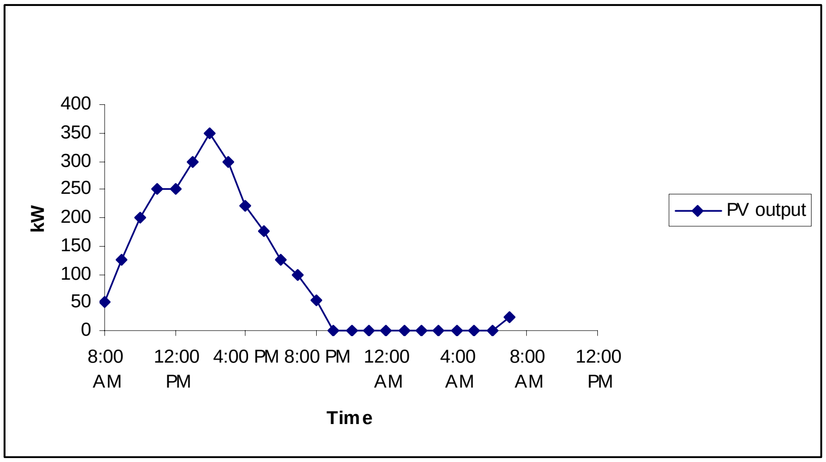

Figure 1.16

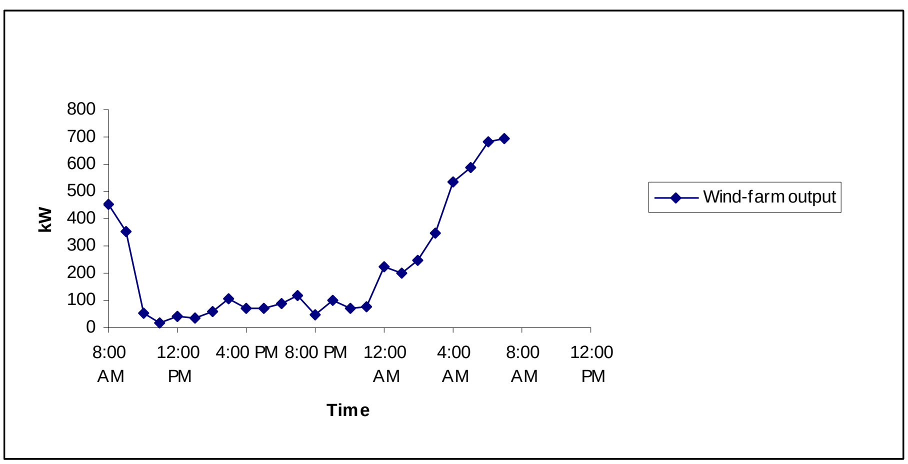

Figure 1.17

Adding the two curves the objective curve to be inputted to the shifting algorithm is obtained. This curve together with the forecasted load for the 6th October 2003 is shown next on Figure 1.18. The situation is specially critical with the minimum forecasted generation output expected at the time of peak demand.

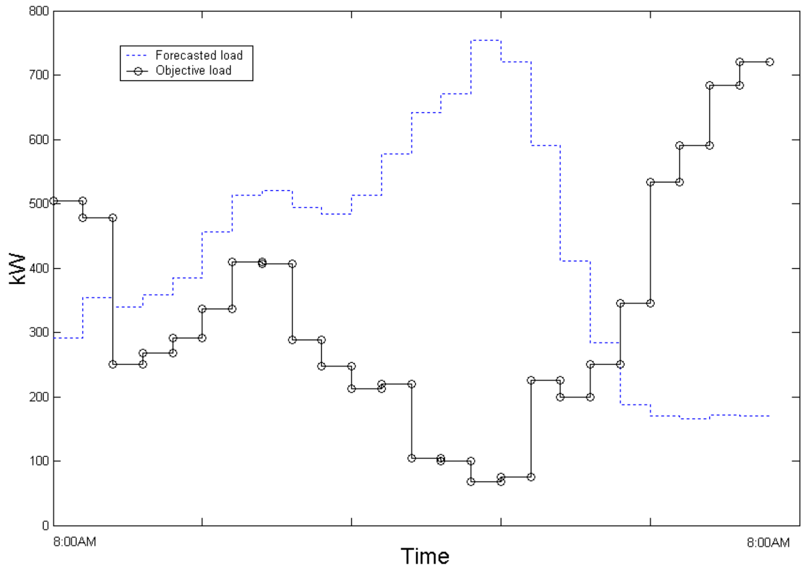

Figure 1.18

The control period goes from 8:00AM to 8:00AM and the controllable load is the same as Figure 1.14. It is formed by 525 washers, 305 dryers and 441 dish-washers.

Considering that the allowable delay of all the appliances is 12 hours, the resulting load curve after the execution of the shifting algorithm is:

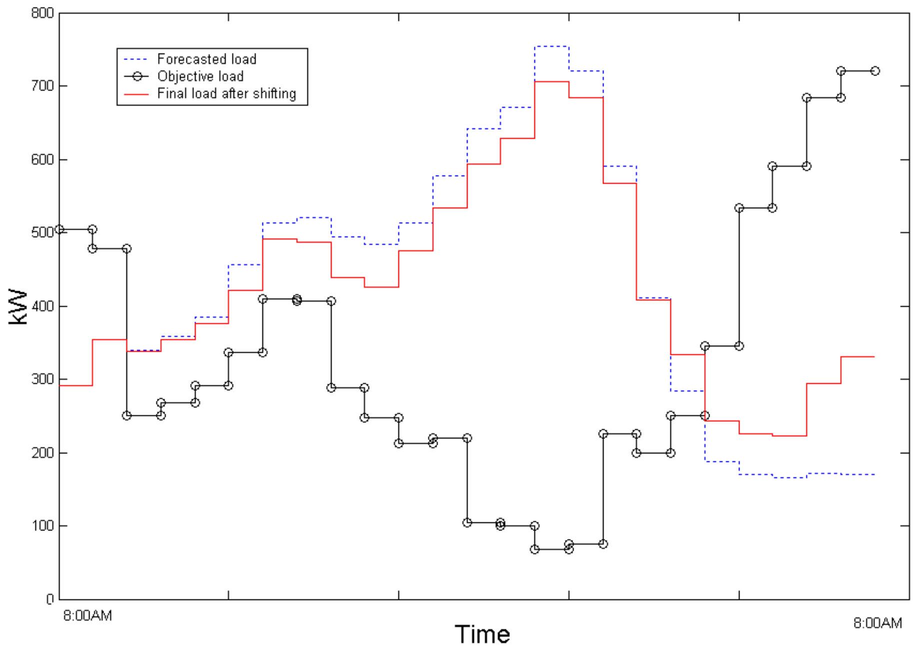

Figure 1.19

Figure 1.19 shows that some benefit is obtained and the final load curve is closer to the objective than the previously forecasted curve. It has to be said that the algorithm cannot act beyond the contracted possibilities and cannot properly fill the night valley hours or completely remove the evening peak. The advantage of the algorithm is that even if the final load might be far away from the objective load curve the situation has been clearly improved. The amount of energy shifted is equal to 500,5 kWh resulting in an improvement of the autonomy of the microgrid.

If the maximum allowable delay is set to 24 hours, the shifted energy becomes 1044kWh.

1.2. Load curtailment

Load curtailment algorithm has been developed with the aim of being run just under exceptional circumstances in emergency conditions. The algorithm schedules curtailment control actions over loads that allow it under contracted conditions and brings the overall load consumption curve as close as possible to a given objective curve. The complete explanation and mathematical formulation of the algorithm are given on deliverable DC1.
The case studies that are presented next have been simulated on Matlab and exemplify the working procedure of the curtailment algorithm.

1.2.1. Base Case

The curtailment algorithm will be installed at the same 1100 customer microgrid of the shifting case studies . In this case the considered data is referred to summer period, when the use of air conditioning is extensive on southern European countries. Figure 1.20 shows a typical daily load consumption curve on July 2003 for the aggregated 1100 customers. The curve is represented from 00AM to 24AM.

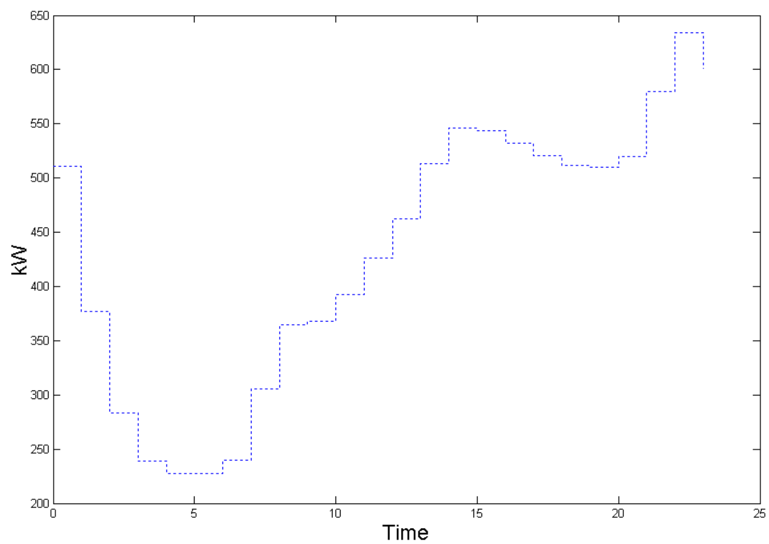

Figure 1.20

Controllable load

On this case the controllable load is just formed by domestic air conditioning units. There are both type1 and type2 air conditioning units. On deliverable DC1 the specific characteristics of each type of curtailable appliance are explained. The main difference is that type1 air conditioning units have a defined and finite duration consumption pattern and type2 air conditioning units are connected all day long.

The consumption patterns of type1 and type2 air conditioners are shown below:

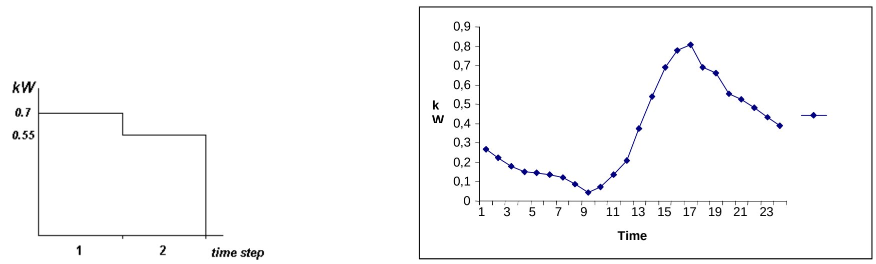

Figure 1.21

Type1 air conditioner is ON for two hours consuming an average of 0.7 and 0.55 kW on each of them. A type2 air conditioner is ON during the 24 hours of the control period. Their consumptions are shown on Figure 1.21.

For each appliance type a diversified curve is provided in the same way as for the shiftable devices. The dissagregation process of the curve for the type1 appliances is exactly the same as the one described on the section dedicated to the shifting base case on this document. In this case the resulting number of type1 air conditioning connections during the 24 hour period is equal to 452.
The dissagregation process for type2 curve is straightforward, the shape of the type2 consumption pattern is the same as the diversified curve and therefore a simple division gives the number of type2 device connections. In this case there are 61 type2 air conditioners connected.

If we consider that by contract we could reduce the consumption of each air conditioner by just a 50%, the final control margin that would be available for the curtailment algorithm is shown shadowed on the next figure:

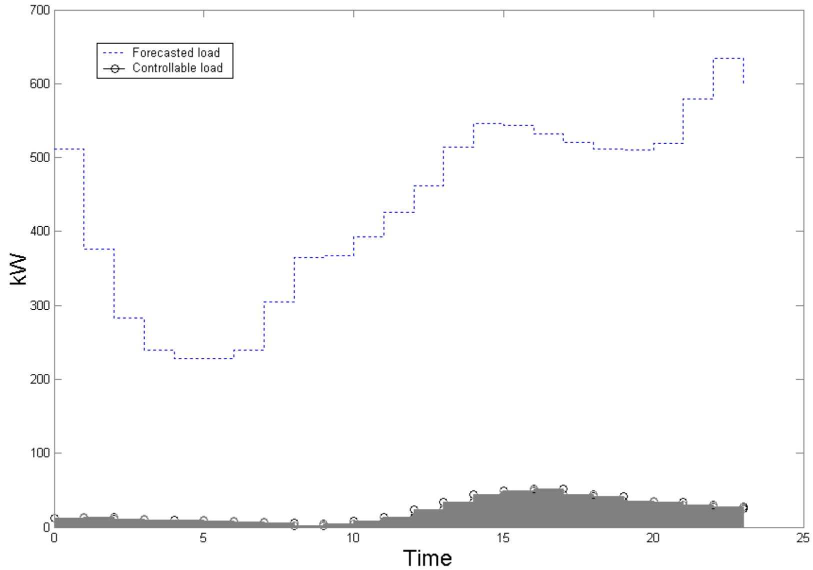

Figure 1.22

1.2.2. Case1

Starting from the previous base case we will consider that at 14:00PM the Microgrid central controller anticipates that during the next two hours there will be an unexpected loss of generation due to extremely low winds and lack of solar radiance. It decides that the load consumption at those 2 hours should be 500kW.
The curtailment algorithm is then launched with a two time step long control period that goes from 14:00PM to 16:00PM.
It will be considered that all the appliances can be controlled just for a maximum of two consecutive hours.

The result is shown on Figure 1.23 and Figure 1.24.

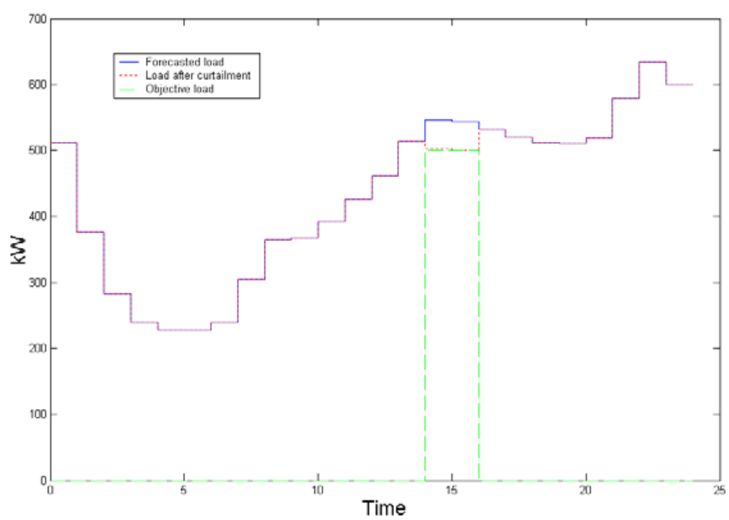

Figure 1.23

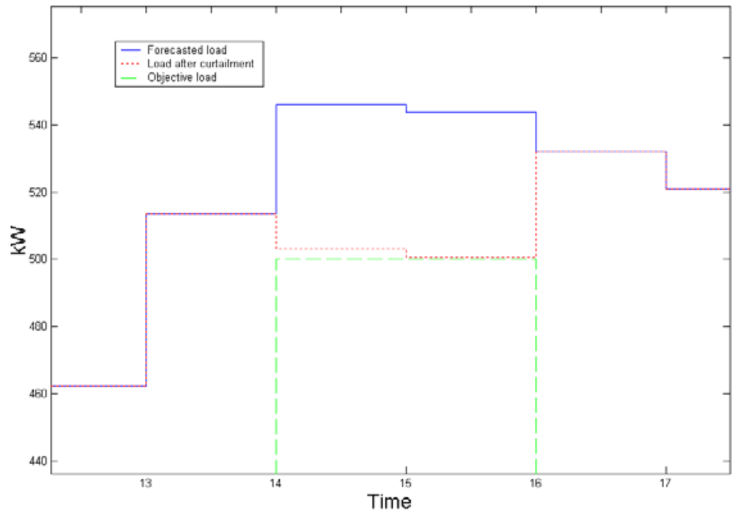

Figure 1.24

Figure 1.24 is a zoom on the curtailment period. It can be seen that the load reduction brings the load curve very close to 500kW. The control actions that have been calculated are explained below:

- Number of type 1 devices that were connected at time step 14 and are not controlled: **0**
- Number of type 1 devices that were connected at time step 14 and are controlled (its consumption reduced a 50%) during 1 hour: **31**
- Number of type 1 devices that were connected at time step 15 and are not controlled: **1**
- Number of type 1 devices that were connected at time step 15 and are controlled (its consumption reduced a 50%) during 1 hour: **7**
- Number of type 1 devices that were connected at time step 15 and are controlled (its consumption reduced a 50%) during 2 hours: **32**
- Number of type 1 devices that were connected at time step 16 and are not controlled: **5**
- Number of type 1 devices that were connected at time step 16 and are controlled (its consumption reduced a 50%) during 1 hour: **37**
- Number of type 2 devices that are not controlled: **1**
- Number of type 2 devices that start to be controlled at time step 15 and are controlled (its consumption reduced a 50%) during 1 hour: **5**
- Number of type 2 devices that start to be controlled at time step 15 and are controlled (its consumption reduced a 50%) during 2 hours: **55**

- Number of type 2 devices that start to be controlled at time step 16 and are controlled (its consumption reduced a 50%) during 1 hour: **0**

These values are the output from the algorithm, including the effect of the truncation to the closest integer.

If we repeat the case study limiting the maximum allowable control duration to one single hour the new result will be:

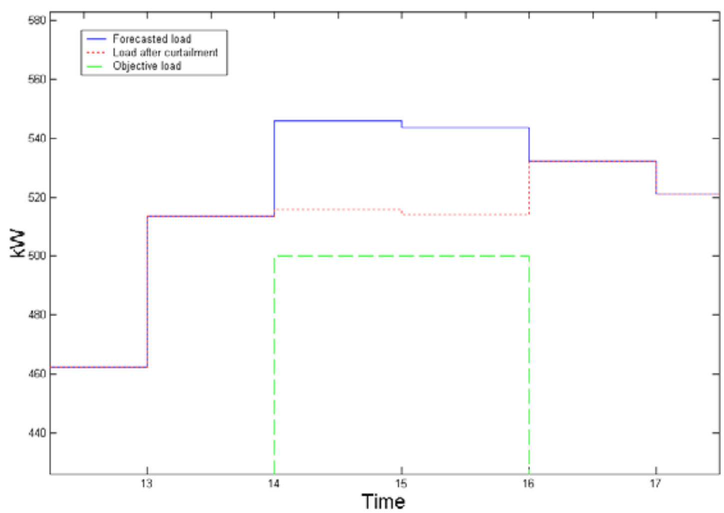

Figure 1.25

In this case the final load curve is approximately 16 kW away from the objective, but the load has been sensibly reduced alleviating the emergency situation to some extent. If the load reduction is still not enough to consider the network state as “safe”, and there is not any possibility to obtain reserve from outside the microgrid or from storage, further load shedding procedures should take place. The calculation and execution of these extra load shedding actions is out of the scope of the curtailment algorithm and will possibly create much more inconvenience to customers.

1.2.3. Case2

In this case study the objective of the curtailment algorithm will be to shave the consumption peak that exists between 22:00PM and 23:00PM. The control period is therefore one hour long and established at time step 23. The objective load consumption is set at 580kW, the same load that was consumed at time step 22. The maximum allowable control duration is set by contract to 2 hours. In this particular case where the control period is only one hour long, as far as the maximum allowable delay is at least one hour this parameter will not have any influence on the result.
The rest of the parameters are the ones defined as base case. Result is presented on Figure 1.26.

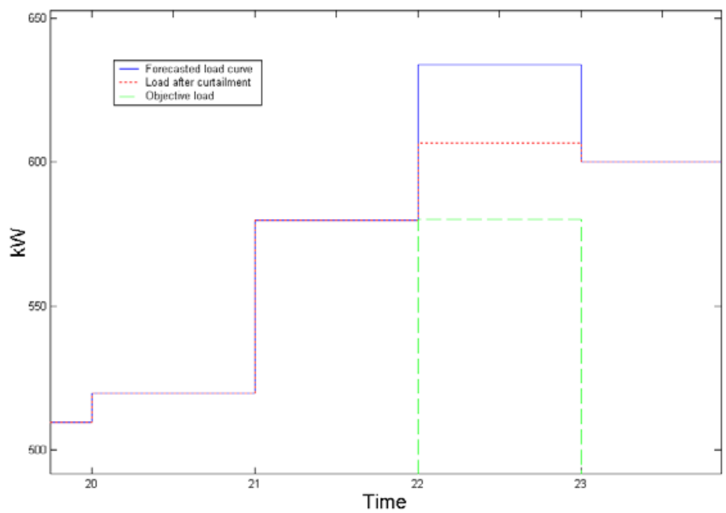

Figure 1.26

The existing control margin proves to be insufficient again and the algorithm does not reach the established objective load.

1.3. Conclusions

Several case studies have been simulated using both shifting and curtailment algorithms. The load shifting algorithm controlling three typical domestic appliances such as washer, dryer and dish-washer proves to be a good tool providing flexibility to change the aggregated load curve on a 1100 customer microgrid.

As the majority of the controllable appliances are connected daily between 7:00AM and 15:00PM the definition of the control period is very important. If we want to have the chance to shift these appliances from their expected connection moment to night valley hours where overall electricity prices are low, the shifting control period should start around 7:00AM and finish at the end of the night.

The contracted control possibilities are a very important factor only if the control period allows it. In general the longer the allowable delay, the bigger the obtained benefit.
Basically the MGCC can play two different roles, according to its relationship with the customers. On the first one the customers under the control of the MGCC are supplied at a fixed tariff and are compensated according to the controllability that they allow over their loads. Taking into account that longer allowable delays require bigger contracted compensations, the delay that provides the best balance between required compensation and obtained benefit will depend on the particular conditions of each particular case and has to be calculated independently.
In the other role the MGCC acts like a service provider in a way that provides savings that are directly related to the controllability of each customer. This second alternative only makes sense if customers are subjected to variable prices and the obtained benefit goes directly to them.

If the objective curve that is inputted to the shifting algorithm is based on prices, big price variability is very desirable. Studies show that the results obtained with price data from the Spanish market (not very variable) are worst than the results of the same studies performed with data from the Amsterdam Power Exchange.
It may be arguable that if we modify a significant part of the load in a power system, prices can be affected. This is not the case if we move in the order of magnitude of a microgrid, but can certainly be true if all the appliances within a country's power system are centrally controlled.

If the objective curve is not only based on economic considerations and is built having in mind the forecasted availability of renewable generation, the algorithm proves to be useful maximising the independence of the microgrid from the main grid.

In terms of curtailment, case studies demonstrate that the curtailment algorithm can be a very useful tool in order to safely accomplish the control of a microgrid. It provides control margin minimising the disturbance caused to end-users.