MORE MICROGRIDS – Advanced Architectures and Control Concepts for More Microgrids

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Business case for Microgrids with economic and environmental evaluation

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1. CONTENTS

2. INTRODUCTION

In this part of the deliverable it is assumed that at least 2 aggregators compete in order to sign contracts for the optimization of operation of Microgrids. The first one, let's say A operates the Microgrid according to Market Policy 1, strictly economically trying to maximize the benefits for the DG sources and his own income. Aggregator B tries to increase his market share by taking advantage of participating in the emissions markets and providing part of the additional benefits to the Microgrids stakeholders. Moreover, additional benefits will be created by losses reduction and the income for this service, increased installation of PVS, and the emissions avoided by losses reduction, which as the reader will see from the following chapters is not negligible. Preliminary studies [1] report that reduction of losses by 1% in the UK system reduces emissions by 2 million tonnes of CO_2 per year. Moreover, in the UK, reduction by 1 GWh from hydrocarbon can reduce emissions up to 400 thousand tonnes per year. In selected Portuguese networks of various types, ranging from rural LV networks to HV ones, 20% penetration of DG sources reduces CO_2 emissions by 2.07% -4.85% [2]. It is also demonstrated that on European scale, 65 million tones of CO_2 per annum can be saved by 50 million installations of domestic CHP units.

Next to the potential environmental benefits of DER, their economic evaluation is critically influenced by the developing CO_2 emissions trading markets [2], which also affect production costs of electricity generated by thermal (hydrocarbon) units [1].

Co-ordinated operation and control of DER can help in obtaining full benefits from their operation. The installation of DER close to loads reduces flows in transmission and distribution circuits and thus losses. Moreover, the increased efficiency of DG sources, especially CHP, and the operation of RES reduces emissions.

A significant impact of increased efficiency in the domestic utilization of gas and electricity on the reduction of CO_2 emissions is claimed in [9].

In this part of the deliverable studies the environmental benefits of the co-ordinated operation of DER under two different optimisation objectives, namely minimising operating costs and minimising emissions. Moreover, the potential benefits from the participation of DER in the CO_2 emission trading markets are calculated. Section 3 presents the adopted methodology for the estimation of the environmental impact from the co-ordinated operation of DG sources. In section 5.1, data for the typical LVs Microgrid and the multi-microgrid environment are presented. The results with regards to pollutants, $CO_{2,}$ $SO_{2,}$ NO_X and Particulate Matter (PM-10) are presented in section 6 for both LV and MV networks. In the same section under the two optimisation objectives and the surplus income obtained by the DER owners from their participation in the Emissions Trading markets. Conclusions are drawn in section 6.2.

3. METHODOLOGY APPROACH

Here the methodology approach followed for calculating the presented results is:

3.1. Power losses estimation

The change in real and reactive power flows caused by microgrids generation has important technical and economic implications for the power system [10]. So, Microgrid generation alters the power flows in the network and so will alter network losses.

If a small Microgrid generation is located close to a large load then the network losses will be reduced as both real and reactive power can be supplied to the load from the adjacent Microgrid generators. Conversely, if a large Microgrid generation is located far away from network loads then is likely to increase losses on the distribution system.

Generally, there are active power losses in the transmission network. These losses depend on the currents in the branches of this network which in turn depend on the voltages, and calculating these voltages is the object of the power flow calculation.

The avoided losses are often pointed out as an important value to be credited to microgeneration. Therefore, the quantification of the impact of microgeneration on losses of transmission and distribution networks is an important issue. Several studies have been made to evaluate the impact of DG on losses as well as to allocate the variations to generators and consumers. Most of those studies are devoted to find out how losses vary in a specific feeder and DG plant connection or when a predefined scenario of DG penetration is considered. Some of those studies propose algorithms to define the optimal location to DG [11],[12].

The Microgrid generation will generally choose to operate at unity power factor to minimize their electrical losses and avoid any charges for reactive power consumption, irrespective of the needs of the distribution network. If a Microgrid generation produces some power at unity power factor the voltage profile is much more satisfactory [10], [13]. The total injected complex power at bus i, denoted by S_i, is given by: $S_i = P_i + jQ_i = V_i I_i^*$. The summation of powers over all buses gives the total system losses:

$$P_L + jQ_L = \sum_i^n V_i \cdot I_i^* = V_{bus}^T \cdot I_{bus}^* \qquad \textbf{(1)}$$

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

3.2. Estimation of environmental benefits

Three (3) cases can be used for evaluating environmental benefits of Microgrids.

ED1: The average yearly emissions values are used for evaluation (g/kWh)

ED2: The average monthly emissions values are used for evaluation (g/kWh)

ED3: Use of marginal emissions curve.

Since the Microgrids penetration in the grids is expected to be relatively low, the initial unit commitment schedule of the centralized production is not expected to change. However, there will be modifications in the economic dispatch of the most expensive, i.e. critical units of the upstream network, and the network losses as calculated with the method described above. Both will alter the emissions of the upstream network. Therefore, in order to estimate the emissions avoided, using average yearly or even monthly values will lead to misleading results, since very rarely will the base units be affected [14]. For this reason, the assessment of environmental impact of Microgrids uses a monthly 24-hour typical emissions curve, *Pol,* depending on the upstream network units' characteristics as provided by the following formula.

$$Pol(hr,m,po)=\frac{\sum_{i=1}^{unno} fcu(hr,m)_i \cdot emf(po)_i}{days(m)} \qquad \mathbf{(2)}$$

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

Typical 24-hour emission curve from the island of Crete for different periods shows the application of equation (2) in Fig. 1.

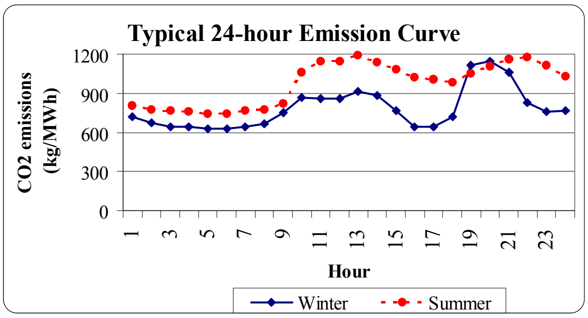

Fig. 1 Typical 24-hour emission curve

Data regarding both DG sources emissions and central units for different fuels can be found in various bibliographic sources [16]- [19].

4. STUDY CASE NETWORK

In this section, data about the study case network, the upstream network and the emissions are provided.

4.1. Description of the LV grid with DER

The typical LV network, shown in Fig. 2 [25], is used in our study. The network comprises three feeders, one serving a primarily residential area, one industrial feeder serving a small workshop, and one commercial feeder. Typical daily load curves for each feeder and the whole Microgrid are shown in Fig. 3. The total annual energy demand is 1160 MWh.

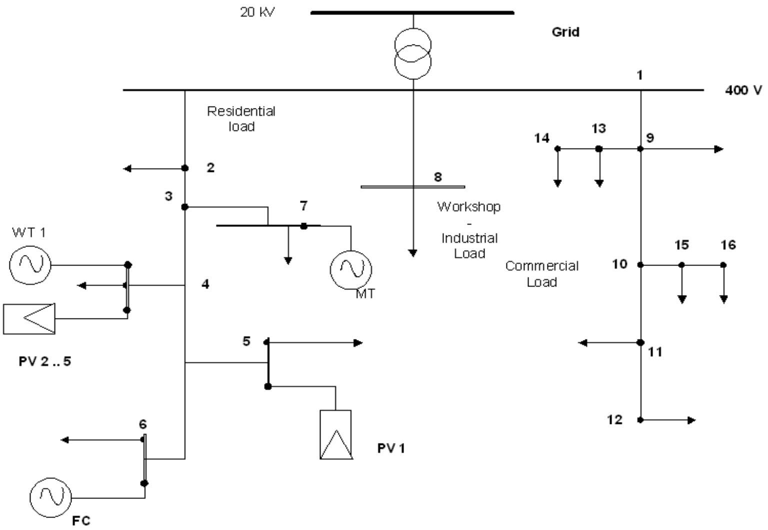

Fig. 2 The study case LV Network

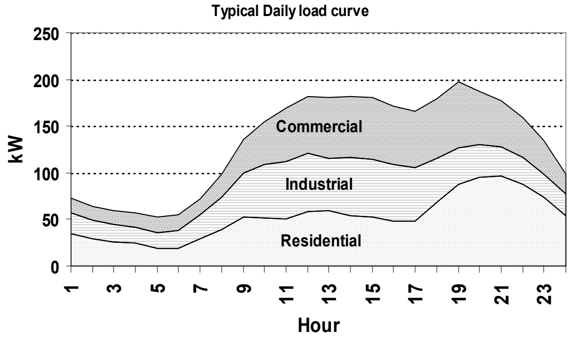

Fig. 3 Typical load curve for each feeder of the study case network

A variety of DG sources, such as one Micro Turbine (MT), one Fuel Cell (FC), one directly coupled Wind Turbine (WT) and several PVs are installed in the residential feeder. It is assumed that all DG sources produce active power at unity power factor, i.e. neither requesting nor producing reactive power. Table 1 provides the capacity of the installed DG sources and their production costs. Both Micro-Turbine and Fuel Cell are assumed to run on natural gas, whose efficiency is 8.8 kWh/m^3 and price 10 c€/m^3 [26]. For the MT the efficiency is assumed 26%, while the efficiency of the Fuel Cell is assumed 40% [27]. Energy prices from the Amsterdam Power Exchange (ApX) for 2003 [28] have been assumed to represent realistically the open market in which the LV grid operates.

Table 1 Installed DG Sources

Unit ID	Unit Type	Max Power (kW)	Production Cost c€/kWh
1	MT	30	4.37
2	FC	30	2.84
3	WT	10	0
4	PV1	3	0
5	PV2	2.5	0
6	PV3	2.5	0
7	PV4	2.5	0
8	PV5	2.5	0

Wind Turbine and PV units are considered always committed and their output is, when available, always injected to the grid. The rest of the units are committed according to a)-c) operation modes. In our case MT and FC production depends on the operation mode followed and is the one that differentiates the emissions and economic savings.

In order to generalise the method used, instead of wind speed and solar radiation data time-series, probabilistic methods of deriving annual and monthly production of wind and PV have been utilised as described below.

For wind speed the Weibull parameters of the installation site and the wind turbine characteristic curve can be used to derive the expected annual wind power production using the methodology described in [29]. In our case study we have assumed Weibull parameters k=2.1 and c=8.1m/s and a 10kW Bergey wind turbine characteristic curve [30]. Under these assumptions the expected wind power production is 28.4 MWh[29].

In order to derive the expected savings from wind power production in a market environment, the wind power production is convoluted with the ApX market prices data for 2003, and the expected savings for the installed wind power as calculated in [29] are 1469.3 **€.**

In order to derive the monthly production of the wind turbine, monthly and annual wind power production data from a reference power system are used as equation (3) describes. Such data are usually available to the public either from the TSO reports [21]. In our case data from annual report of the Cretan Power system have been used [31].

$$Month\_WP\_tur = \frac{Annual\_WP\_tur}{Annual\_WP\_ref\_sys} \cdot Monthly\_WP\_ref\_sys \qquad (3)$$

where *Month_Wp_tur* is the monthly production of the wind turbine,
Annual_WP_tur the annual wind turbine production.
*Annual_WP_ref_sy*s and *Monthly_WP_ref_sys* are the annual and monthly wind power production of the reference power system, respectively.

Solar radiation data for Athens have been used and the expected monthly solar power production has been calculated using the equations in [29]. For the installed PV capacity the production is 15.2 MWh and using the convolution with ApX prices the savings due to PV operation are 1267.37 €.

For the monthly demand data, annual demand is distributed to each month according to the Reliability Test System weekly variation [32] and the typical demand curve of the Microgrid, as shown in Fig. 3. Both the monthly demand and production of RES sources of the studied LV network are given in Table 2.

Table 2 Monthly Demand and Production data in MWh

	Demand	Wind	PV
Jan	104.33	3.14	0.82
Feb	100.92	2.17	0.95
Mar	87.88	2.06	1.33
April	89.54	2.05	1.52
May	100.38	2.75	1.72
June	104.33	3.24	1.72
July	104.62	1.75	1.75
Aug	97.75	1.69	1.65
Sept	91.08	2.8	1.2
Oct	87.49	1.86	1.05
Nov	88.35	2.27	0.79
Dec	104.36	2.9	0.68

Wind and solar energy sources have zero direct emission during their operation. Fuel burning DER, like biogas units using tyres or agriculture residues, may even have higher emission levels than the ones of the central units [18]. Table 3 summarises the emissions of typical fuel consuming DG sources, assuming that they run on Natural Gas.

Table 3 Typical emission data for various DG-sources (kg/MWh) [19]

Pollutants	**MT**	**FC**	**GT**	**ICE**
CO_2	724.6	489.4	678.2	650
NO_X	0.2	0.014	0.521	2.13
SO_2	0.004	0.003	0.004	0.206
PM-10	0.041	0.001	0.039	0.354

4.2. Typical MV network

A step forward is to consider many Microgrids operating in a typical radial MV (Medium Voltage) network, shown in Fig. 4. This network consists of two (2) parallel transformers of 25MVA, a typical size of many HV/MV substations in many semi-rural areas in Greece. The typical MV distribution network is derived from a physical MV network of Greece [20], which supplies a small town and the surrounding rural area at a rated voltage level of 20 kV supplied from a 150kV transformer station. The total number of LV Microgrids similar to Fig. 2 is 64 in 8 feeders. The MV network structure consists of 130 nodes. The base voltage may be modified to study different voltage levels as long as the chosen values are realistic. The line length is 1km from bus to bus and they can be modified as long as the typical MV distribution network character is retained. Resistances and reactances of the MV network lines can be found in Table 4. On 20kV network and at buses the maximum capacity of dispersed generator is 6,5-10MVA [10].

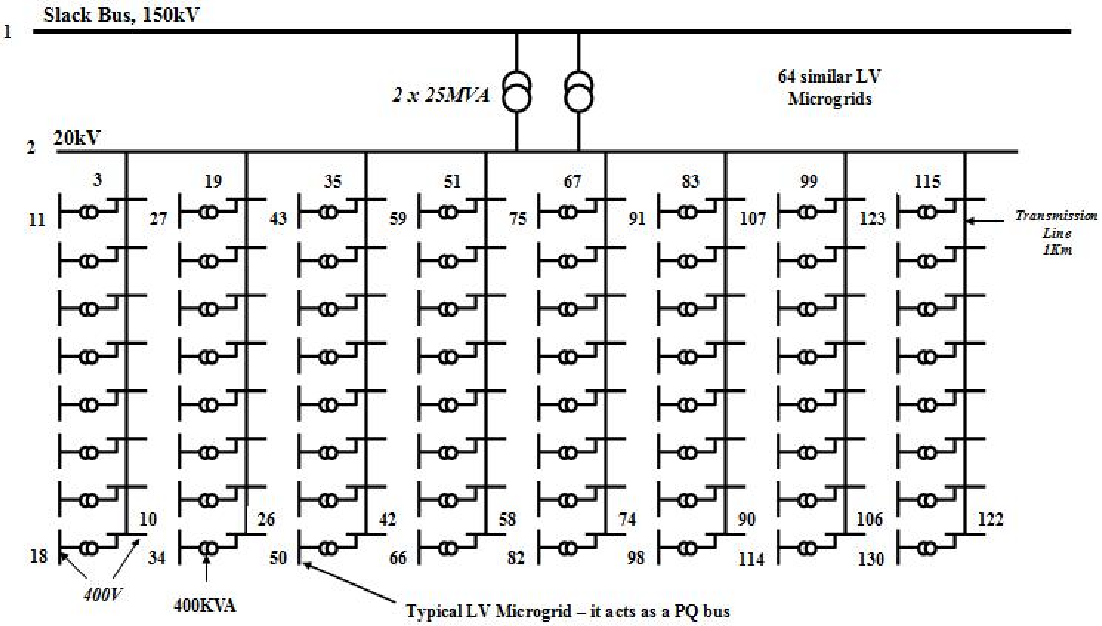

Fig. 4 The MV network considered for multi-Microgrids environment

Table 4 Electrical characteristics of MV transmission lines (20kV).

Conductors	3x50 Al+50 St (TC)
R (Ω/km)	0,823
X (Ω/km)	0,150
(jB) B (μS/km)	45,867
Imax (A)	123

4.3. Power System Connected

The LV network studied is assumed to operate connected to the power system of Crete. This is the largest island system in Greece with a variety of generating units, i.e. steam turbines, diesel units, gas turbines and one combined cycle unit using oil. For this system complete hourly time-series of load, production units and wind power production for year 2001 are available. From this, 24-hour emission curves can be derived for each month. Table 5, provides data about the average emissions of the power system of Crete in year 2001 and Table 6 summarises the monthly emissions. It is noted that during the summer months, when the gas turbines mostly operate consuming diesel oil with relatively low sulphur content, SO_2 emissions are reduced, but NO_X is increased [31].

Table 5 2001 Average annual Emissions of Crete (kg/MWh)

Pollutants	Annual Emissions
CO_2	809.4
SO_2	7.85
NO_X	2.25
Particulate Matter (PM-10)	0.501

Table 6 2001 Average Monthly Emissions of Crete Power System (kg/MWh)

	CO_2	SO_2	NO_X	PM-10
January	802.1	8.23	1.62	0.449
February	805.6	7.49	1.61	0.440
March	824.9	7.87	1.75	0.445
April	823.9	8.24	1.63	0.457

May	806.4	8.10	1.56	0.455
June	791.7	7.98	2.43	0.443
July	800.8	7.32	3.65	0.442
August	799.5	7.16	3.47	0.441
September	787.8	7.51	3.69	0.439
October	797.09	7.62	2.90	0.442
November	812.94	8.56	2.60	0.458
December	861.60	8.66	2.87	0.486

Table 7 provides the annual emissions for each type of unit operating in Crete. The peaking units are the old gas turbines, while in medium load conditions the new gas turbines are the marginal units. During low load conditions, e.g. spring nights, quick response units, gas turbines and diesels do not operate and only the must-run units steam and Combined Cycle unit operate. In such a case the marginal unit is the Combined Cycle (CC) unit.

Table 7 2001 Average Annual Emissions for Crete by type of unit (kg/MWh)

	CO_2	NO_X	SO_2	PM-10
Steam	964.7	1.09	17.50	0.59
Diesel	545	10.5	10.2	0.35
Combined Cycle	632.59	1.21	0.206	0.309
Old Gas turbines	1230	2.35	0.42	0.6
New Gas Turbines	861	1.65	0.28	0.42

The emission rate for each fuel type used and the specific consumption of each unit of the power system in kg/MWh or kg/GJ can be taken into account to estimate the avoided emissions. For the power system of Crete average fuel emissions per fuel are provided in Table 8. For other types of fuel, average emissions can be found in [16].

Comparing Table 1 and Table 7 it can be seen that the Fuel Cell has significantly lower emissions than all the types of units on Crete. On the other hand, the MT CO_2 emission level is higher than the corresponding emissions of both the Diesel and the Combined Cycle unit, but lower than the monthly or annual CO_2 emission levels.

Table 8 Emissions level for the two different types of fuels used in Crete

	Average Emissions (kg/Tn)	
	Heavy Oil	**Diesel**
Particles	1.86	1.19
SO_2	57.12	0.80
NO_X	11.4	4.67
CO_2	3200	2445

5. SCENARIOS CONSIDERED

3 Scenarios are considered in our analysis contrary to business as usual scenario (BAU) of the strict economic operation:

1. Microgrid participating in CO_2 emissions market
2. Subsiding installation of double PV capacity
3. Transfer of the MT at another feeder

5.1. Microgrid participating in CO_2 emissions market

A significant opportunity for DER to increase their operation and reduce their pay-back period is participation in the CO_2 emission trading market. DER can offer CO_2 reduction to the upstream grid and thus they can operate during periods that their operating cost is higher than the market cost, provided they are sufficiently remunerated for CO_2 emission reductions as the equations below describe. Results from this analysis are given in 6.1.3.

Assuming that DER participate in the CO_2 emissions market, their marginal costs are accordingly modified to take into account fuel cost and the income due to CO_2 emission savings, as follows:

$$marginal\_cost = operational\_cost - Emissions\_avoided \cdot Emission\_cost \qquad (4)$$

The operational cost is the bid of the unit, as provided in Table 1, and the *Emissions_avoided* is the difference between the emissions of the DER unit from the grid emissions in kg/MWh. The *emission_cost* is the financial incentive from the emissions trading market, mainly applied for CO_2 and usually expressed in €/tn.

Three cases are considered for the *Emissions_avoided,* depending on the available CO_2 emissions data for the upstream network.

- Case 1 (SCE 1): The annual emission level is considered constant for the whole year and the CO_2 remuneration is based on it.
- Case 2 (SCE2): Every month, the monthly CO_2 emission level is communicated to DER and the remuneration is based on the calculated emissions avoided.
- Case 3 (SCE3): The calculated 24-hour emission curve, as described in (2), is communicated to DER, every month. Thus DER are given an incentive to produce during hours with significant CO_2 emissions as described by the emission curve.

For instance for the FC, the *marginal_cost* is calculated for the different scenarios as:

28.4 €/MWh-(809.4-489.4)kg/MWh*x €/kg	SCE1
28.4 €/MWh-(802.1-489.4)kg/MWh*x €/kg	SCE2
28.4 €/MWh-(*Emissions(hour,month)*-489.4)kg/MWh*x €/kg	SCE3

,x is the CO_2 emissions trading price.

Using the methodology described in section 2, the emissions avoided in the above cases (SCE1-SCE3) can be calculated, as well as the financial gains and can be compared to the revenues obtained by the economic operation and optimal environmental operation. Different values for CO_2 emissions trading prices have been considered ranging from 5 to 60 €/tn and the results are presented in the following sub-sections 6.1.3.

6. RESULTS

6.1. Emissions avoidance

6.1.1. Without DER

6.1.1.1. Emissions and Network losses

The network losses are calculated at 19.1MWh per year or 1.63% of the annual losses. The emissions due to the supply of the demand of the LV Microgrid without DER would produce the annual emissions shown in Table 9 based on more realistic values in ED3. In the same table the emissions due to losses are provided. Losses account for similar percentage in emission losses.

Table 9 Annual Emissions to satisfy centrally the Microgrid Demand

Pollutants	Emissions due to demand(kg)	Emissions due to losses (kg)	Sum emissions (kg)
CO_2	1,065,871	18114	1,083,985
SO_2	351.9	6	357.9
NO_X	2,040	34.7	2,074.7
PM-10	520	8.9	528.9

6.1.2. Minimization of Operating Costs –Business as Usual

It is assumed that RES are priority dispatched and the dispatch of the other DER is based on economic criteria. It is calculated that the MT operates for 22% of the year and the FC for 48.66%, when their operating costs (Table 1) are lower than the open market prices. The annual production of the DER is 231.48 MWh. Additionally, 3.67MWh of annual losses are avoided equal to 19.27% of the initial losses. The emissions avoided are presented in Table 10.

Table 10 Emissions avoided by DER when minimizing operating costs

Pollutants	Emissions Avoided (kg)			Emissions Avoided (%)
	Production	Losses	Total	
CO_2	114328.1	3612.15	117940.3	10.88
SO_2	71.75	6.94	78.69	20.38
NO_X	419	1.2	420.2	20.53
PM-10	116.79	1.77	118.56	22.42

6.1.3. Operation taking into account the participation in emission markets

6.1.3.1. Change in operating hours and emissions

For our case study the difference in savings, DG production and emissions comes from the change in consumption of Fuel consuming units, in our case FC and MT.

The following tables summarize the operating hours and the production of the FC and MT in the 3 cases and for different prices for CO_2 avoided emissions in €/Tn.

6.1.3.2. SCE1

In this case, the remuneration for CO_2 avoidance is based on the calculations under ED1,that is why the values are evaluated according to this methodology as well. The change in the operating hours and production for the FC and MT are presented at Table 11.

Table 11 Annual operating hours and Production of FC and MT - SCE1

CO_2 price (€/tn)	FC		MT		Total Microgrid Production (MWh)
	Operating Hours	Production (MWh)	Operating Hours	Production (MWh)	
0	4299	128.97	1955	58.65	231.49
5	4611	138.33	1957	58.71	240.91
10	4947	148.41	2008	60.24	252.52
15	5353	160.59	2045	61.35	265.81
20	5776	173.28	2076	62.28	279.43
30	6643	199.29	2163	64.89	308.05
50	8048	241.44	2399	71.97	357.28
60	8376	251.28	2497	74.91	370.06

FC operating hours are significantly increased, as the CO_2 trading value increases, and are almost doubled when the CO_2 trading price is 60 €/tn. On the other hand, MT operation is not much influenced due to its higher emission level. Its annual operating hours and production are increased by maximum 27.7%.

It is interesting to examine the impact on the avoided emissions not only for the assumption used for the remuneration, ED1, (Table 12) but also for the most realistic case of marginal emission curve of Table 14.The actual emissions avoided are by about 30tn of CO_2 per year higher. Much lower are SO_2 emissions finally avoided than the expected values.

Table 12 Emissions change under ED1- SCE1

CO_2 price (€/tn)	CO_2 (kg)	NOx (kg)	SO_2 (kg)	PM-10 (kg)
0	81757.74	497.67	1816.49	109.2
5	84758.03	518.72	1890.41	113.54
10	88113.37	544.4	1981.51	118.94
15	92105.1	573.91	2085.8	125.1
20	96244.76	604.19	2192.67	131.4
30	104789.3	667.7	2417.25	144.67
50	118877.7	776.46	2803.55	167.6
60	122275.8	804.49	2903.83	173.59

Table 13 Emissions change under ED3- SCE1

CO_2 price (€/tn)	CO_2 (kg)	NOx (kg)	SO_2 (kg)	PM-10 (kg)
0	114328.06	419	71.75	116.79
5	118707.43	437.73	74.94	121.54
10	123159.25	458.01	78.38	126.63
15	128247.34	480.62	82.22	132.35
20	133184.91	503.19	86.05	138.06
30	142237.14	548.36	93.7	149.45
50	154308.55	620.46	105.87	167.53
60	157058.12	638.93	108.99	172.11

6.1.3.3. SCE2

In this case, the remuneration for avoided CO_2 is based on the calculations under ED2. The operating hours and production for both the FC and MT are presented at Table 14.

Table 14 Annual operating hours and Production of FC and MT – SCE2

CO_2 price (€/tn)	FC		MT		Total Microgrid Production (MWh)
	Operating Hours	Production (MWh)	Production (MWh)	Operating Hours	
0	4299	128.97	58.65	1955	231.49
5	4611	138.33	58.8	1960	241
10	4955	148.65	60	2000	252.52
15	5366	160.98	61.32	2044	266.17
20	5740	172.2	62.79	2093	278.86
30	6622	198.66	65.64	2188	308.17
50	8013	240.39	72.18	2406	356.44
60	8376	251.28	75.36	2512	370.51

The increase in operating hours and DER production is similar to SCE1. In this case the emission level is known at monthly level, therefore there is sufficient information allowing the use of monthly emission levels (ED2). The analysis based on annual emissions is not considered and only results for the analysis based on ED2 and ED3 are presented in Table 15 and Table 16, respectively.

Table 15 Emissions change under ED 2-SCE2

CO_2 price (€/tn)	CO_2 (kg)	NOx (kg)	SO_2 (kg)	PM-10 (kg)
0	81416.77	568.64	1814.95	100.92
5	84776.86	596.19	1901.25	105.81
10	88243.85	624.68	1994.47	111.03

15	92343.7	658.89	2102.56	117.14
20	96097.47	691.11	2203.09	122.8
30	104813	762.84	2434.21	135.84
50	118719.4	876.89	2814.36	157.22
60	122452.7	909.05	2926.14	163.4

Table 16 Emissions change under ED 3- SCE2

CO_2 price (€/tn)	CO_2 (kg)	NOx (kg)	SO_2 (kg)	PM-10 (kg)
0	114328.06	419	71.75	116.79
5	118678.25	437.82	74.95	121.56
10	123100.05	457.79	78.35	126.59
15	128230.45	480.91	82.27	132.42
20	132754.36	502.08	85.86	137.75
30	142097.68	548.59	93.74	149.48
50	153981.9	619.16	105.65	167.19
60	157099.5	639.64	109.12	172.28

Change in estimations of emissions due to more detailed information (ED3) in this case are similar to the ones of SCE1.

6.1.3.4. SCE3

This case cannot be implemented as easily as the other two cases, since it requires information on a typical 24 hour emission curve for the main grid for the specific month to be transmitted to the DG sources. This information however, helps in the reduction of CO_2 emissions, since it can increase remuneration during these hours, based on the marginal emissions of the upstream grid.

Table 17 Annual operating hours and Production of FC and MT – SCE3

CO_2 price (€/Tn)	FC		MT		Total Microgrid Production (MWh)
	Operating Hours	Production (MWh)	Operating Hours	Production (MWh)	
0	4299	128.97	1955	58.65	231.49
5	4679	140.37	2029	60.87	245.11
10	5148	154.44	2170	65.1	263.41
15	5537	166.11	2289	68.67	278.65
20	5843	175.29	2416	72.48	291.64
30	6317	189.51	2709	81.27	314.65
50	7138	214.14	3363	100.89	358.9
60	7455	223.65	3665	109.95	377.47

It can be noted that the operating hours for MT are significantly increased (almost doubled) compared to the previous 2 scenarios. This is due to the correlation of the hours with high emission rates with attractive market prices that makes MT participation in the open market beneficial. The decrease in Marginal cost of the MT, as calculated by (4), may even reach 30 €/MWh for 60 €/tn CO_2 prices when an old Gas turbine is the marginal unit of the system contrary to maximum reduction of 8.22 €/MWh obtained for December for SCE2. Thus, there is significantly higher possibility that the MT under SCE3 will have lower marginal cost than the open market prices compared to the previous two scenarios.

On the other hand, the operating hours of the FC are not so much increased, as in the previous 2 scenarios. The maximum decrease in marginal cost may be even more significant during high emission hours but, during these hours, FC will also probably operate for SCE 1 and 2. For SCE3, during some hours, the difference between FC emissions and main grid is lower compared to SCE1 and SCE2 leading to higher marginal cost compared to SCE1 and SCE2. Thus the operating hours at SCE 3 are not so much increased compared to economic operation as in the other two scenarios. However, the total production of the whole Microgrid is increased at all cases for SCE3 compared to SCE1 and SCE2.

Since 24-hour emission curve is available, avoided emissions can be calculated according to ED3 and results from this analysis are presented at Table 18.

Table 18 Emissions change under ED3 SCE3

CO_2 price (€/tn)	CO_2 (kg)	NOx (kg)	SO_2 (kg)	PM-10 (kg)
0	114328.1	419	71.75	116.79
5	121305.7	434.33	76.68	124.01
10	129090.4	467.21	82.47	132.47
15	135414.1	494.3	87.23	139.45
20	140147.1	516.32	91.12	145.12
30	147587.7	554.12	97.87	154.88
50	160468.1	624.66	110.58	173.11
60	165423.7	653.59	115.82	180.6

In the next subsection 6.1.3.5 the revenues and CO_2 emission savings are summarised and compared among the studied cases.

6.1.3.5. Income calculations- A comparative approach

Based on the results of subsection 6.1.3, total savings of the DER, shown in Table 19, are calculated.

Table 19 Revenues

CO_2 price (€/tn)	Revenues (€)		
	SCE 1	SCE 2	SCE 3
0	13549.14	13549.14	13549.14
5	13964.31	13964.52	14117.84
10	14396.25	14397.01	14724.13
15	14848.13	14849.74	15365.65
20	15317.96	15320.5	16034.62
30	16322.18	16326.11	17434.88
50	18565.43	18571.25	20227.2
60	19773.32	19778.89	21371.67

Remuneration for cases SCE1 and SCE2 is similar, with differences less than 10 €. More significant increase in earnings can be obtained in SCE3, reaching 58% of the savings compared to optimal economic operation or 7822.53 €/year for 60 €/tn emission trading prices. Percentage savings under different values and CO_2 emission trading prices can be seen in Fig. 5

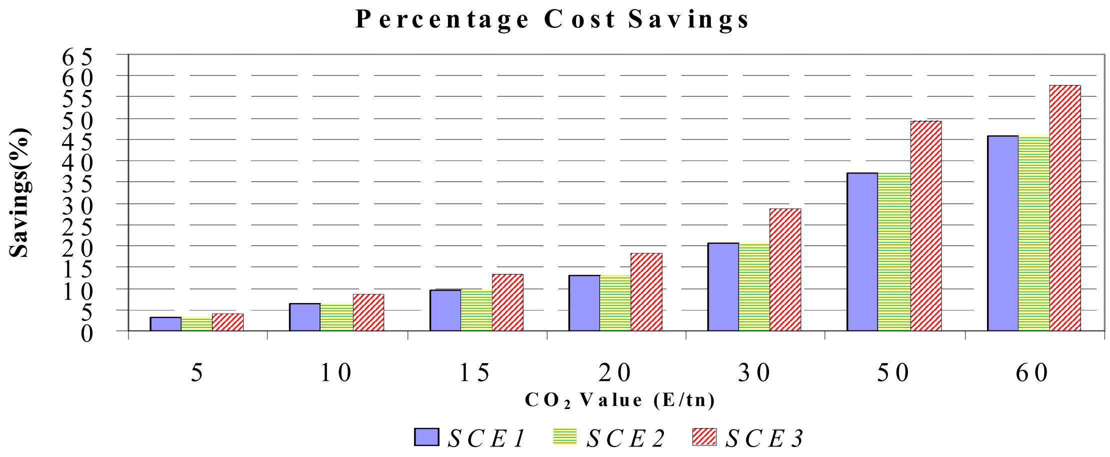

Fig. 5 Changes in Savings of the Microgrid under different scenarios and different prices for CO_2 compared to no participation to the Emissions market.

Table 20 summarises the CO_2 emissions avoided in the three different scenarios evaluated by ED3 methodology, which more realistically represents the emissions from the upstream network.

Table 20 CO_2 reduction under different CO_2 emission prices and different scenarios.

CO_2 price (€/Tn)	CO_2 (Tn)		
	SCE 1	SCE 2	SCE 3
0	114.33	114.33	114.33
5	118.71	118.68	121.31
10	123.16	123.1	129.09
15	128.25	128.23	135.41
20	133.18	132.75	140.15
30	142.24	142.1	147.59
50	154.31	153.98	160.47
60	157.06	157.1	165.42

Fig. 6 presents savings in CO_2 using the ED3 for the emission levels of the network. Differences between different scenarios are now smaller than in the revenue case. For SCE3 the maximum reduction in CO_2 emissions is 45%. Savings can be obtained for other kind of pollutants as well, reaching up to 56% for NOX, 55% for PM-10 and 10% for SO_2.

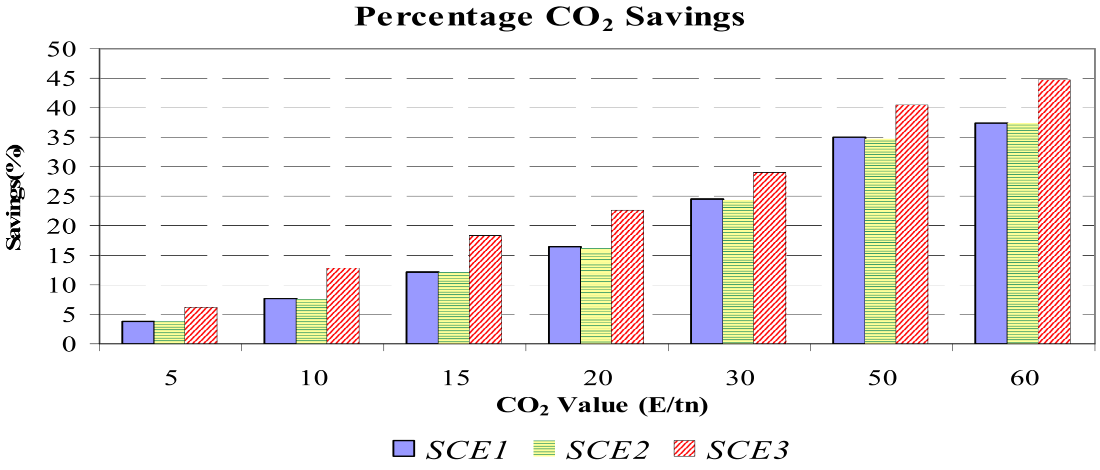

Fig. 6 Savings in CO_2 under different scenarios and prices using Ed3 for the emission levels compared to no participation to the Emission markets.

A typical value for CO_2 exchange market used in several studies is 20 €/tn [34]. Fig. 7 summarises the 4 pollutants emissions avoided as calculated according to ED3 under the three operating scenarios, (SCE1-3) and optimal environmental and optimal economical operation. The emissions avoided are significantly higher for SO_2, NOx and PM-10 compared to the no-DER operation, ranging from 20% in the economic driven operation to 40% in the environmental driven operation. CO_2 avoided is lower ranging between 10.5% and 17%.

In order to compare the savings from adopting the scenario of sub-section, over the optimum environmental and "optimum" economic operation, the CO_2 compensation should be taken into account for both cases. To do so, the calculated CO_2 emissions corresponding to each case scenario should be taken into account. This means that, for instance, to compare SCE1 the emissions based on ED1 should be considered, because according to them, the Microgrid trades the CO_2 emission reduction, for the other scenarios the same approach is followed, compares the savings for this operation and Fig. 8 focuses on the difference between optimum economic and SCE1-3 operation.

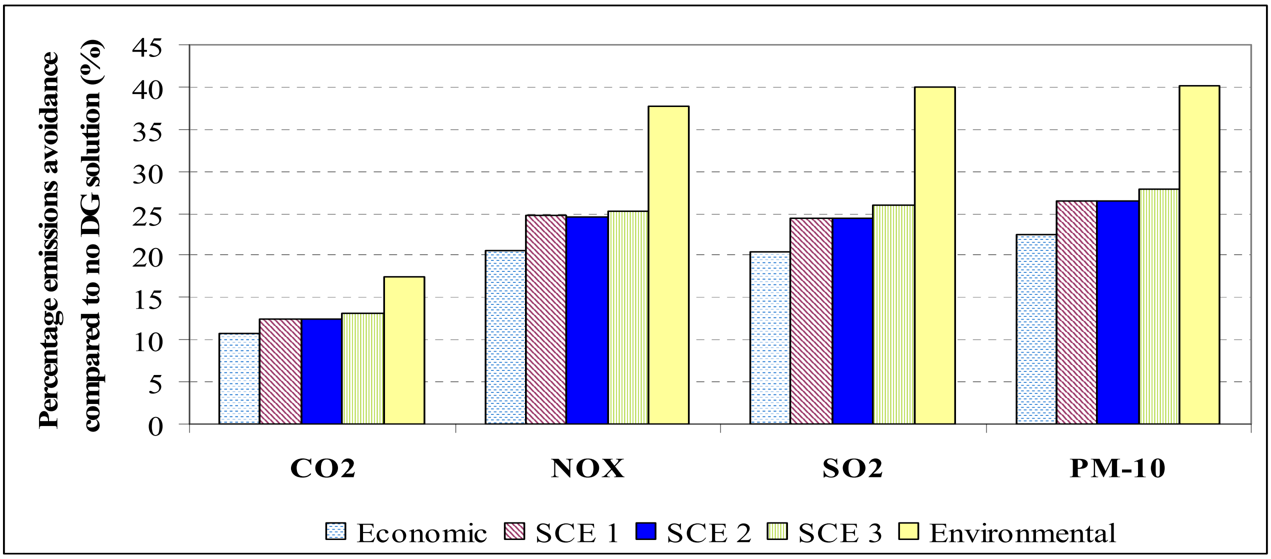

Fig. 7 Comparison of Emission savings compared to no DG sources under the operating scenarios studied using CO_2 emissions value 20 €/Tn [34]

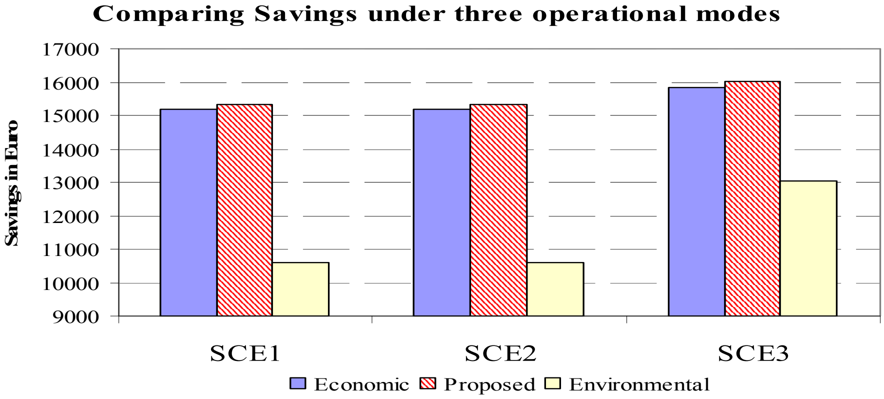

Fig. 8 Comparison of cost savings compared to no DG sources under the operating scenarios studied assuming CO_2 emissions value 20 €/tn

It can be seen that in all cases operation under the proposed Scenarios SCE1-3 increases the savings for the Microgrid by up to 200 €, or about 1% compared to economic operation considering market prices only and the CO_2 remuneration as an additional income that is welcome but not an optimisation goal.

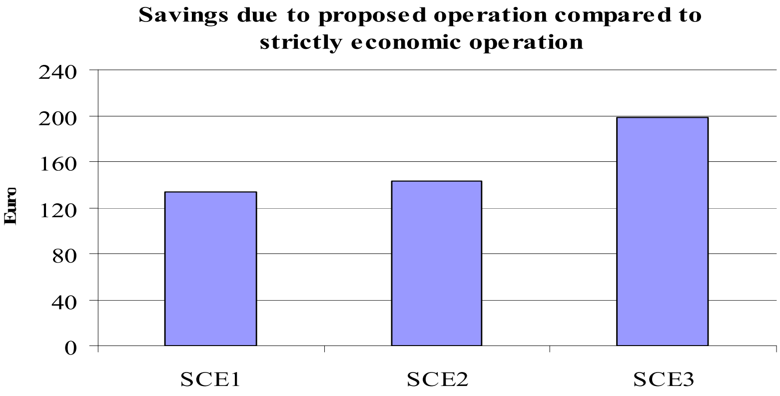

Fig. 9 Comparison of cost savings between economic and proposed operation assuming CO2 emissions value 20 €/tn

6.1.4. Income due to additional losses avoided

The fact that more DG units operate when sufficiently remunerated for emissions reduction further reduces losses on the LV lines and thus creates additional income for the Aggregator by both the value of active power bought from the network and the emissions avoided due to losses reduction.Table 21 sumarizes the additional income created by operating Microgrids based on CO_2 remuneration incentive compared to both BAU and strict economic operation with passive remuneration of the emissions avoided at the same price..

Table 21 Summary of additional income and losses with remuneration of 20 €/tn

	Absolute Values	**Percentage Values**
Additional Production emissions Avoided	25.82Tn CO_2	22.59%
Additional Income compared to no remuneration	2485.48€	18.34%
Additional income due to aiming at more environmental operation	198€	1%
Additional Losses Avoided (kWh)	1090	29.7%
Value of losses Avoided	46.46€	18.49%
Additional Emissions avoided due to additional losses avoidance	1.1tn	6.06%
Value of emissions avoided due to losses	21.97€	6.06%
Sum of additional income compared with BAU scenario and remuneration for emissions passively avoided	266.43€	1.97%
Sum of additional income avoided compared to BAU scenario without emissions remuneration	2553.91€	18.84%

6.2. Doubling PV capacity

In order to study increase of PV capacity, an issue that it is expected in Southern Europe we consider that the installed PV capacity is twice as much as the installed PV capacity of network in Fig. 2.

The expected production is 1170 kWh/kWp while the expected income is 97.49€/kWp. The average price for the whole year is 8.34 €ct/kWh. Next figures present the hourly losses during a typical winter, spring, and summer day. Losses avoidance for various typical days and months is shown in Fig. 10-Fig. 12.

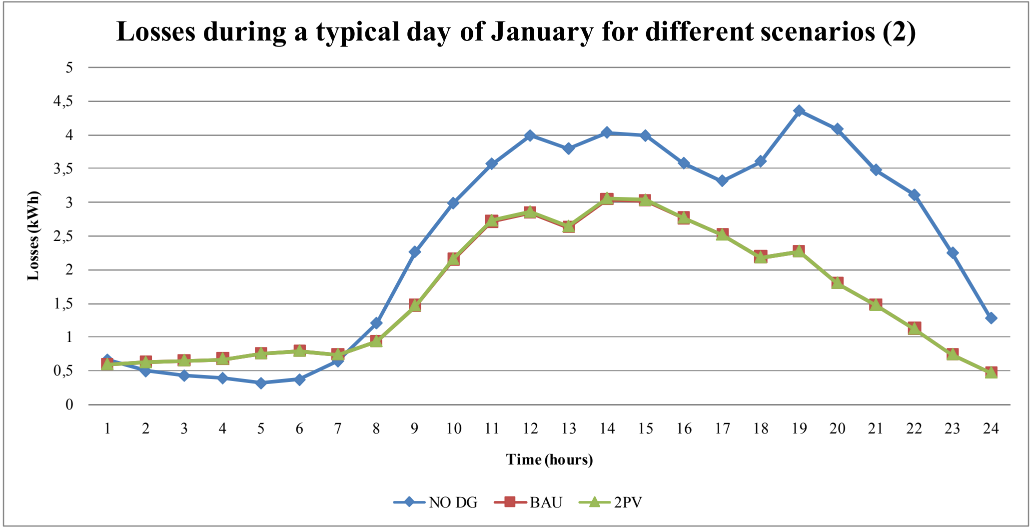

Fig. 10 Losses with doubling PV production during a typical winter day

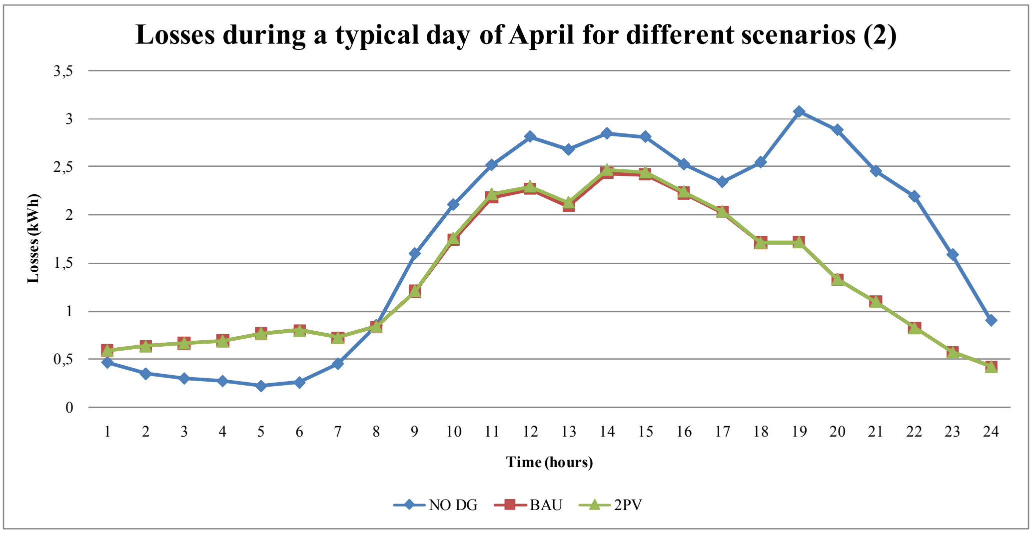

Fig. 11 Losses with doubling PV production during a typical spring day

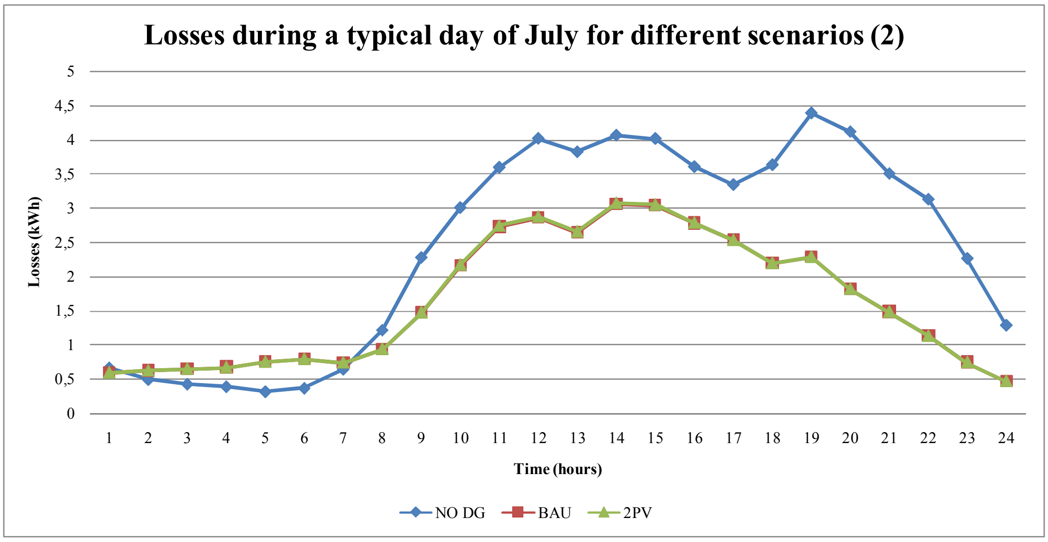

Fig. 12 Losses with doubling PV production during a typical summer day

6.2.1. Additional Losses and emissions avoided

Installation of PVs will alter flow on the network lines especially during daytime when they are expected to be higher from the grid to the customers of the micro grid. The expected total losses avoided for the whole year are 3.82MWh or 19.96% of the losses without DER. Compared to operation with business as usual scenario the additional losses avoided are 158kWh or 0.58% of the annual losses.

Table 22 presents the additional losses avoidance due to installed PV capacity and the additional losses avoided. Emissions avoidance due to losses avoidance is increased by about 0.6% making them less important parameter than the losses avoidance due to production. Thus finally emissions avoidance is by 14.8tn higher for CO_2 compared to economic operation only.

Table 22 Emissions avoided due to doubling PV capacity

Pollutants	Emissions Avoided (kg)			Emissions Avoided (%)
	Production	Losses	Total	
CO_2	129212.7	3724.1	132936.8	12.26
SO_2	76.6	1.2	77.8	20.45

NO_X	447	7.2	454.2	20.53
PM-10	111.7	1.8	113.5	21.47

6.2.2. Final monetization

The additional value of PV production is 1148.7€. If the emissions trading price is 20€/tn, then the additional income due to increasing PV installation is 297.28€ and the money value of additional losses avoidance is 5.49 €. Thus the final income due to additional PVs will be 1451.44€ per year compared to BAU scenario.

The Value of each kW to be installed for the Aggregator is 1323.5€ if we assume 6% interest rate and 20 years of life is which is very low according to current practices even with subsidy. As a result, the PV investment for a 20-year zero Net Present Value with a typical interest rate of 6% is 17,205€.

6.3. Transfer Micro Turbine to another feeder

Under this scenario, the MT is transferred to industrial feeder. The reason for that is the additional reduction of active losses at this feeder which is expected to become higher. Finally the losses avoided are 4.82MWh/year or 25.38% of the initial network losses. Therefore, in terms of losses this transfer is much more efficient than adding PV capacity in the feeder where significant DG capacity already exists increasing the losses avoidance achieved by 31%. This is clearly shown for early afternoon hours shown in these typical days of Fig. 13-Fig. 15.

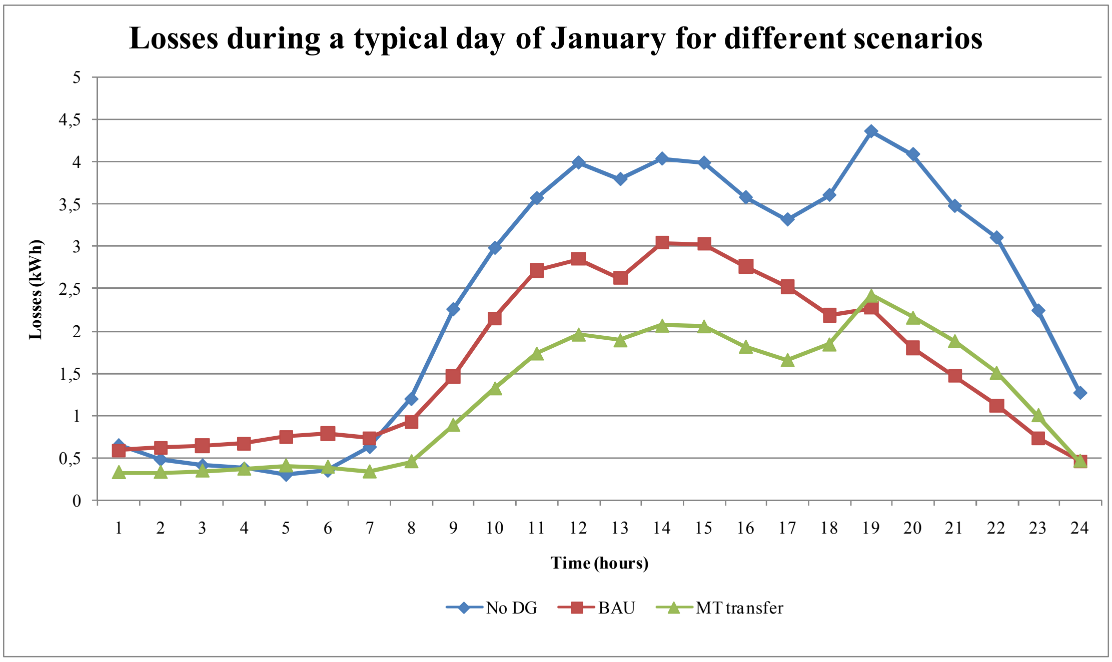

Fig. 13 Losses with MT transfer production during a typical winter day

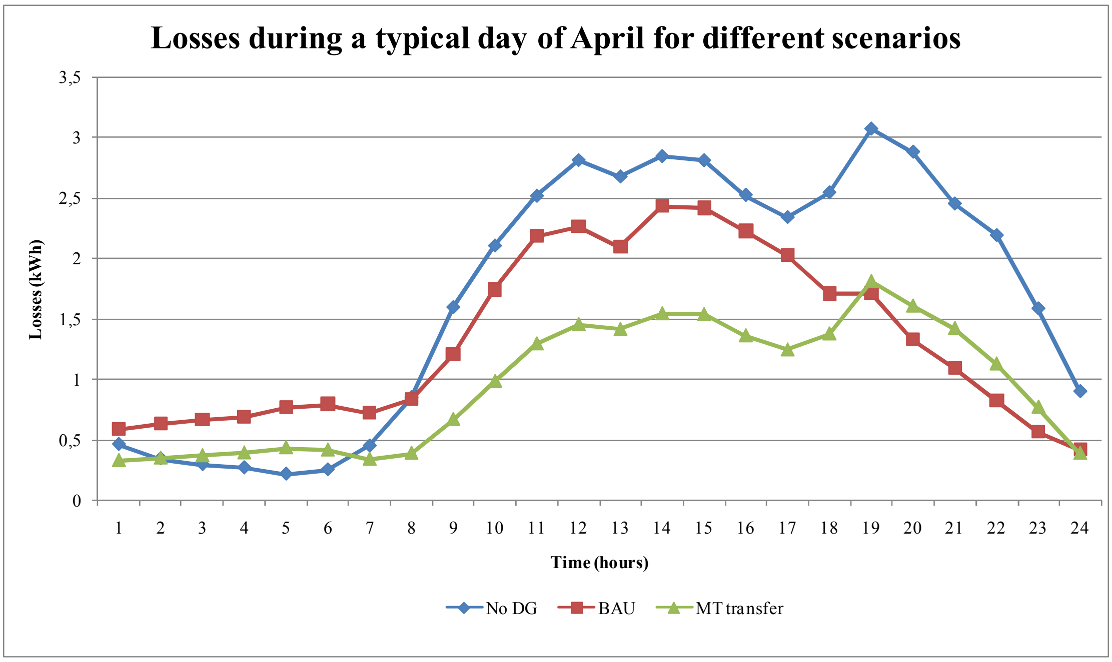

Fig. 14 Losses with MT transfer production during a typical spring day

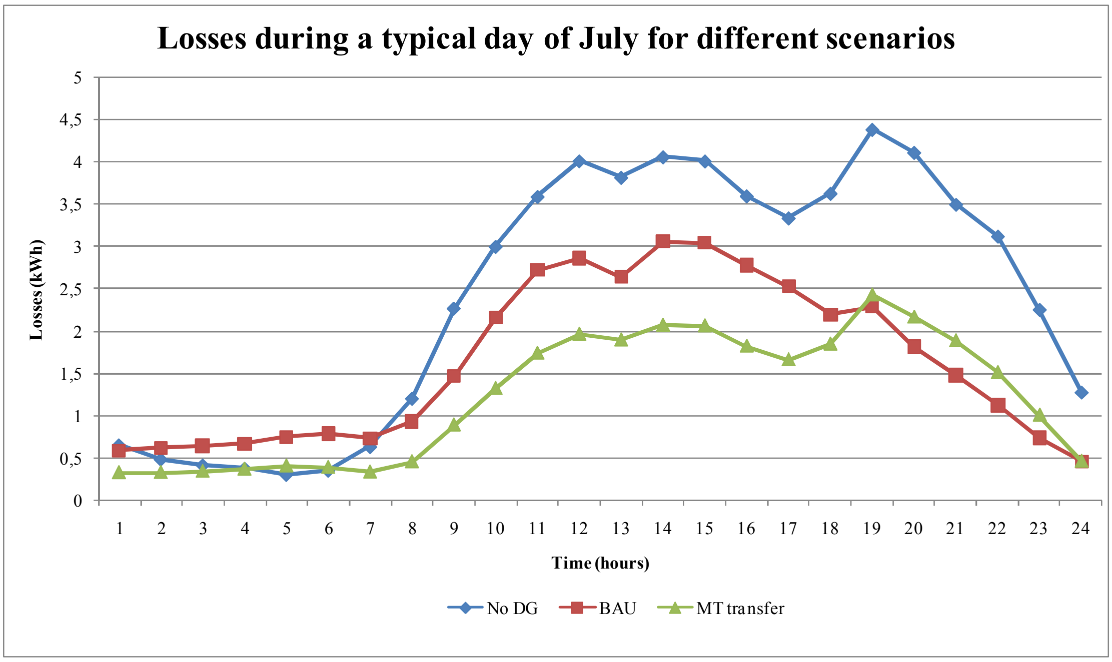

Fig. 15 Losses with MT transfer production during a typical summer day

This losses reduction has clear impact on the emissions finally avoided as Table 23 shows.

Table 23 Emissions avoided due to transferring MT at another feeder

Pollutants	Emissions Avoided (kg)			Emissions Avoided (%)
	Production	Losses	Total	
CO_2	114328.1	4758.6	119086.7	11
SO_2	71.75	1.58	73.33	20.56
NO_X	419	9.13	428.13	20.64
PM-10	116.79	2.33	119.12	20.22

There is no additional income due to sales to the upstream networks, as in the other two cases. The only income comes from monetization of losses and the monetization of additional emissions finally avoided as shown in Table 24.The increase in benefits reach 0.92% compared to BAU scenario.

Table 24 Emissions avoided due to transferring MT at another feeder

	Absolute Values (€)	Percentage
Losses Value	353.49	2.61%
Losses Value vs BAU addtional Income	102.27	0.75%
Income due to Emissions Avoidance compared to BAU	22.93	0.17%
Total additional Income vs BAU	125.22	0.92%

As a result, the MT investment for a 20-year zero Net Present Value with a typical interest rate of 6% is 1434 €. This corresponds to the incentive that customer at feeder 8 should be given to move to another feeder than selecting the residential feeder.

6.4. Comparisons

6.4.1. losses of each scenario

The following figures illustrate the yearly losses of each scenario and the reduction of the losses in comparison with the absence of DG, which means zero production from RES, MT and FC.
It is obvious that there is a significant reduction, which varies from 10% up to 50%. Furthermore, it is clear that we have to sacrifice the losses reduction in order to achieve the most economical operation of the system. Finally, the MT transfer seems to be the best way to reduce the losses due to the topology of the grid (we place the production near to the load).

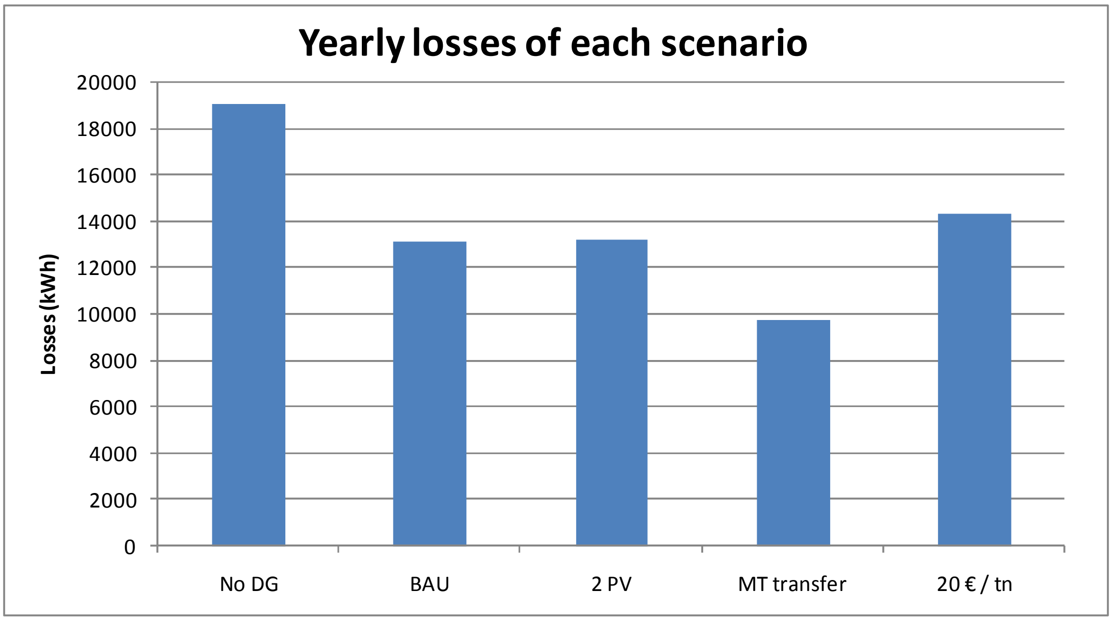

Fig. 16 Yearly losses of the three scenarios

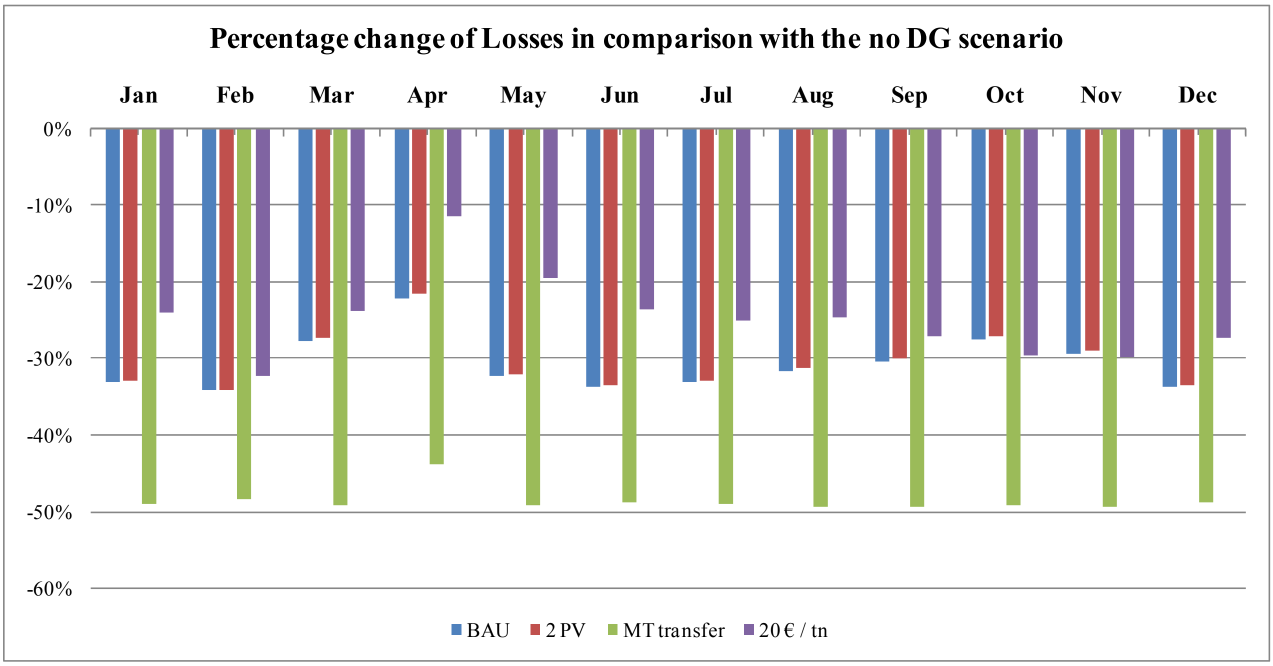

Fig. 17 Percentage change of losses from the scenario with DG absence

6.4.2. Emissions avoidance

A summary of the emissions finally avoided due to the scenario studied is shown in Fig. 18. Clearly motivation in participating in CO_2 emissions markets has environmental benefits over even doubling PV capacity.

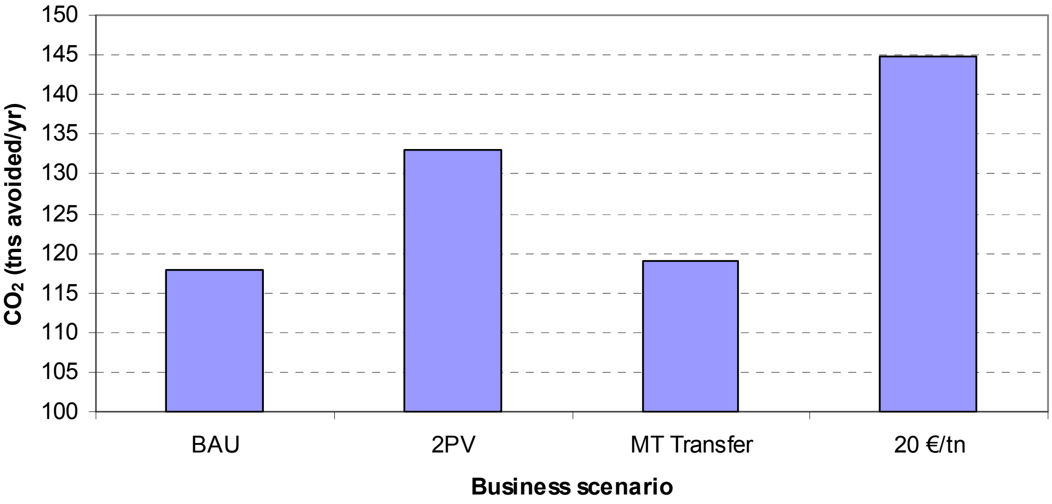

Fig. 18 Percentage change of losses from the scenario with DG absence

6.4.3. Monetization of benefits

The economic difference compared to BAU with remuneration of CO_2 considered in all cases is shown in Fig. 19. If in BAU, remuneration of CO_2 is not considered and the new aggregator would like to take it into account, the economic benefits will be shown in Fig. 20. In all cases CO_2 remuneration is 20€/tn.

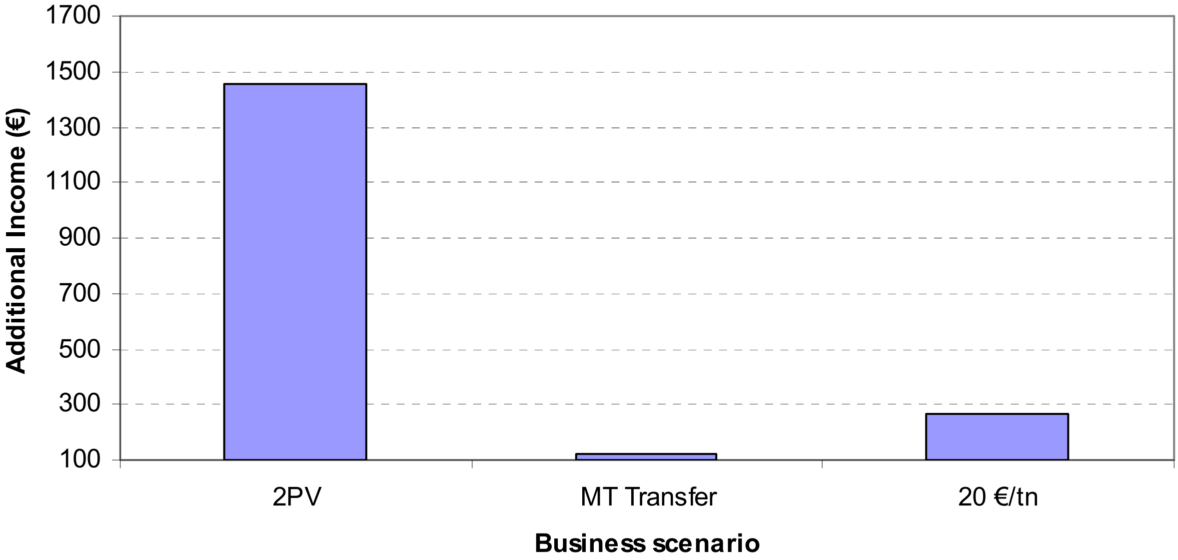

Fig. 19 Additional income for the business case scenarios considered (CO_2 remuneration included in all cases and BAU)

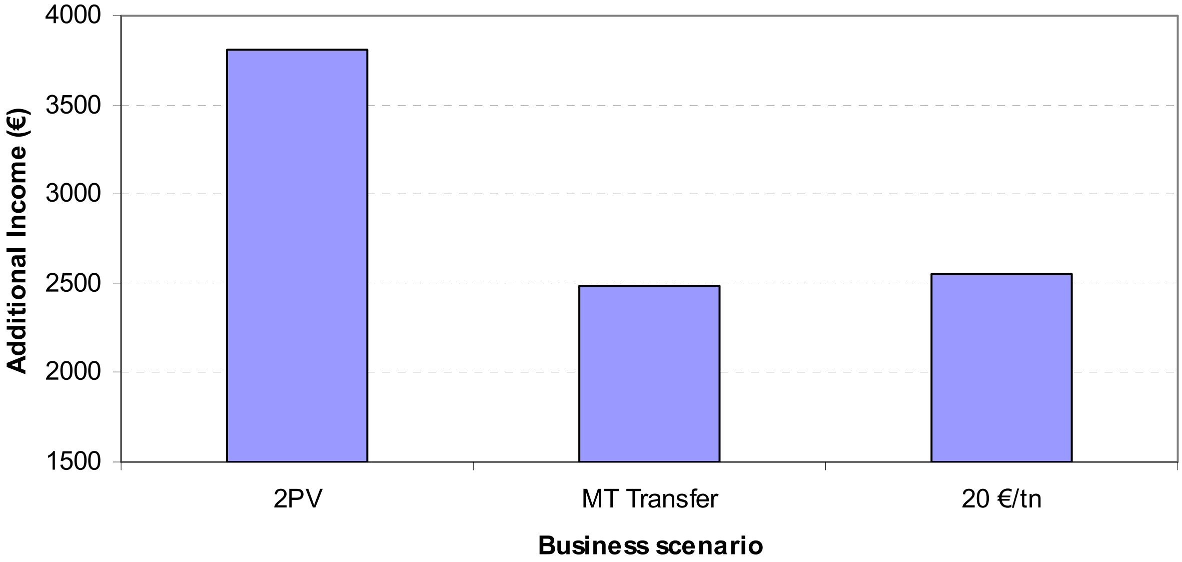

Fig. 20 Additional income for the business case scenarios considered (CO_2 remuneration not included in BAU)

7. CONCLUSIONS

In this report, the capabilities of co-ordinated operation of DG sources to reduce the pollutant emissions of a power network are investigated. Optimal economic operation and optimal environmental operation are studied together with the effect of participation in CO_2 emissions trading, both with respect to emissions reduction and increase of earnings. Application of the developed method depends on the available information regarding emissions of the operating units. The most accurate results are obtained when the emissions and operating intervals of the marginal units are available. Since this is not always the case, monthly or even yearly average emissions values can be used instead, producing however results of lower accuracy.

Although the goal of DER operation might be minimisation of CO_2, the error in the estimation of pollutants may not lead to achieving it, due to the fact that the average emission level leads to operation of DER during hours that are not actually environmentally better. Additionally, this error may lead to revenue reduction. Moreover, for power systems with low average CO_2 emission level, information on marginal units operation would lead to operation of DER during the hours that they can actually reduce emissions. Otherwise, it is possible that DER will not be committed at all.

Operation aiming at maximum emissions savings may reduce DER earnings and thus can be unattractive for DER, unless sufficient remuneration for the emissions avoided is provided. Participation of DER in the CO_2 emissions trading can offset the reduction of DER earnings while reducing CO_2 emissions. It is proven that aiming to maximise the earnings from combined participation in energy and CO_2 emissions market provides significantly higher environmental and economic benefits compared to maximising the earnings from participating only in energy market and considering the CO_2 remuneration as an additional income.

Finally, co-ordinated operation of DER helps in the application of economic and environmental policies, further improving DER benefits. The environmental benefits of such operation may be even higher if fuel consuming units operate in CHP mode, increasing energy efficiency and if the losses reduction is also taken into account.

The results of the losses modeling, especially the ones with full production of the Microturbine, Fuel Cell and the RES (Wind turbine and PV) depict the great impact of the DG on the losses reduction. This reduction, especially in the case where the MT is connected to another bus (bus8), approaches to 49% in comparison with the No DG scenario. As a result, bus8 is a better point of connection for the MT in the Microgrid. Furthermore, it is obvious that the doubling of the PV production does not reduce radically the losses. This is partially justified due to the Microgrid's topology and the low PV installed power in comparison with the value of the losses. Doubling of PV production seems to be economically and environmentally more efficient rather than an investment in MT.

As a general remark can be drawn that in any change in business model, participating in Co2 emissions market in parallel with any other action can increase the benefits achieved.

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