

# **Advanced Architectures and Control Concepts for MORE MICROGRIDS**

**Specific Targeted Project**

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**WPH. Impact on the Development of  
Electricity Infrastructure**

**DH2. Report on economic, technical and  
environmental benefits of Microgrids in typical  
EU electricity systems**

**Annex H2.A.  
Microgrids in Northern and Central Europe  
scenarios:  
Impact studies for typical distribution  
networks with Generic Distribution System  
(GDS) models**

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**Annex H2.A** to Deliverable DH2. “Report on economic, technical and environmental benefits of Microgrids in typical European electricity systems”: **Microgrids in Northern and Central Europe scenarios: Impact studies for typical distribution networks with Generic Distribution System (GDS) models.**

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## **ACRONYM LIST**

AM	Active Management
CHP	Combined Heat and Power
DG	Distributed Generator
GDS	Generic Distribution System
GSP	Grid Supply Point
LV	Low Voltage
PV	Photovoltaic
RES	Renewable Energy Sources

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## 1. Introduction

This Annex summarizes the work performed by Imperial College London to assess the impact of Distributed Generation (DG) in general and Low Voltage (LV) MicroGrids specifically on distribution network infrastructures in Northern and Central Europe. Two types of scenarios are presented: i) scenarios provided by the partners of the project and ii) generic scenarios more specific to LV MicroGrids. The analysis has been carried out by means of the Generic Distribution System (GDS) application, specifically developed by Imperial College London to assess the impact of DG and Active Management (AM) on distribution networks on a system-level basis. The network parameters of the model have been tuned through the data provided by the partners for each country.

The first stream of analysis is based on the data provided by the project's partners according to the template described in Deliverable DH1. More specifically, typical networks for Germany, Poland, and Netherlands have been studied using the envisaged generation/demand scenarios as provided by the partners (and including DG at all voltage levels). A general common characteristic of the scenarios analysed is the presence of Combined Heat and Power (CHP) systems as the main generation technologies within MicroGrids at both LV and Medium voltage (MV) levels, which differs for the Southern Europe scenarios illustrated in Annex H2.B and dominated by Photovoltaic (PV) units.

The second stream of analysis is based on the same network data provided by the project's partners but is more specific to LV MicroGrids consisting of Micro CHP and PV systems. More specifically, typical networks for Germany, Poland, Netherlands, FYROM, and UK have been studied using similar parametric scenarios that can highlight the features and benefits of LV MicroGrids on the entire power distribution network.

Hence, on the one hand it is possible to provide a realistic representation of the evolution of potential infrastructure replacement strategies (with active and passive network management and LV and MV MicroGrids) at all voltage levels, based on the envisaged demand/supply scenarios of each country and, on the other hand, it is possible to provide sensitivity analyses on the impact of LV MicroGrids only on the system evolution, regardless of the actual forecast. In addition, as mentioned in the main Deliverable DH2, two different approaches have been undertaken for system evaluation, namely, a *dynamic assessment* of network evolution, and a *snapshot-based assessment* of network impact (see the main part of Deliverable DH2 for further details).

The Annex is organized as follows:

- Chapter 2 discusses the analysis for Germany;
- Chapter 3 discusses the analysis for Poland;
- Chapter 4 discusses the analysis for Netherlands;
- Chapter 5 discusses the analysis for FYROM;
- Chapter 6 discusses the analysis for the UK;
- Chapter 7 presents a comparative analysis of the results for the different countries and the concluding remarks.

## 2. Distribution Network Analysis for Germany

### 2.1 German Scenarios

#### 2.1.1 General Information

Rather than an average estimate, the total peak load and the relevant information for a specific MVV Energie network have been provided, with a peak load of 484 MW in 2010, and with breakdown by voltage level given in Table 2.1. The load growth given is 0.68% per annum. Basic network information is given in Table 2.2. The DG penetration levels for 2010, 2015, 2020 and 2030 are shown in Figure 2.1. In addition, Figure 2.2 shows the breakdown by voltage level for the different DG types.

<b>Maximum load in GSP</b>	484MW	100%
<b>Maximum load at 0.4kV</b>	159MW	33%
<b>Maximum load at 11kV</b>	213MW	44%
<b>Maximum load at 132kV</b>	112MW	23%

Table 2.1. Maximum load per voltage level

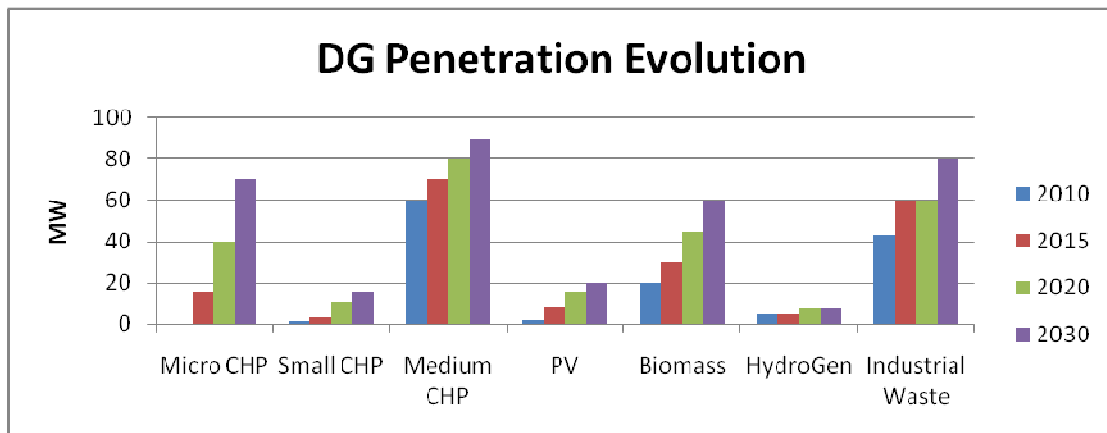


Figure 2.1. Basic penetration evolution.

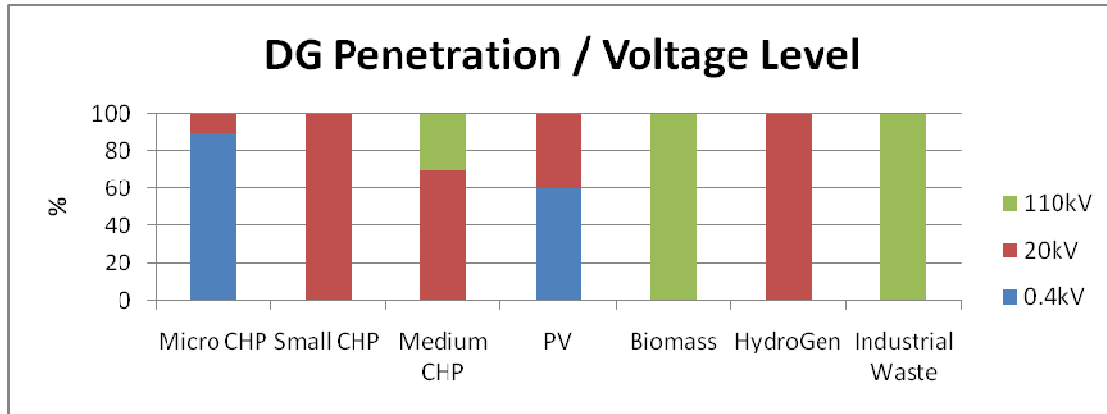


Figure 2.2. DG penetration per voltage level.

Voltage level	0.4kV	20kV	110kV
<b>Number of model types</b>	7	5	4
<b>Number of each model type per GSP</b>	Model 1: 264	Model 1: 8	Model 1: 1
	Model 2: 304	Model 2: 8	Model 2: 1
	Model 3: 112	Model 3: 8	Model 3: 1
	Model 4: 112	Model 4: 12	Model 4: 1
	Model 5: 56	Model 5: 2	
	Model 6: 14		
	Model 7: 14		
<b>Number of total modules per GSP</b>	876	38	4
<b>Number of circuits per model</b>	Model 1: 9	Model 1: 5	Model 1: 2
	Model 2: 8	Model 2: 6	Model 2: 2
	Model 3: 5	Model 3: 7	Model 3: 2
	Model 4: 6	Model 4: 6	Model 4: 2
	Model 5: 3	Model 5: 6	
	Model 6: 6		
	Model 7: 2		
<b>Total number of circuits</b>	6320	228	4*2=8
<b>Total number of transformers</b>	876	8*3=24	no number is given, the transformers do not belong to MVV Energie, there are several 200, 250 and 300 MVA transformers
<b>Capacity of transformers / models (MVA)</b>	Model 1: 0.4	Model 1: 31.5*3	
	Model 2: 0.63	Model 2: 31.5*3	
	Model 3: 0.4	Model 3: 40*3	
	Model 4: 0.63	Model 4: 40*3	
	Model 5: 0.315		
	Model 6: 0.4		
	Model 7: 0.63		

Table 2.2. Structure of the German distribution network

### 2.1.2 Benefits Related to Losses

From information received from MVV Energie, the actual annual losses of the network under investigation are 64GWh while the total imported energy from the GSP is 2500GWh. This information is similar to the annual 61.2GWh of losses and 2428GWh of imported energy calculated using the GDS application. Figure 2.3 shows the total reduction in network losses after the introduction of DG. As DG penetration increases much faster than load (load increases only 0.68% per annum), the reduction in losses increases in the future.

Figure 2.4 presents the total losses reduction per voltage level after introduction of DG. It is noted that losses in the 20 kV network increase as there is a significant amount of DG connected at that voltage level.

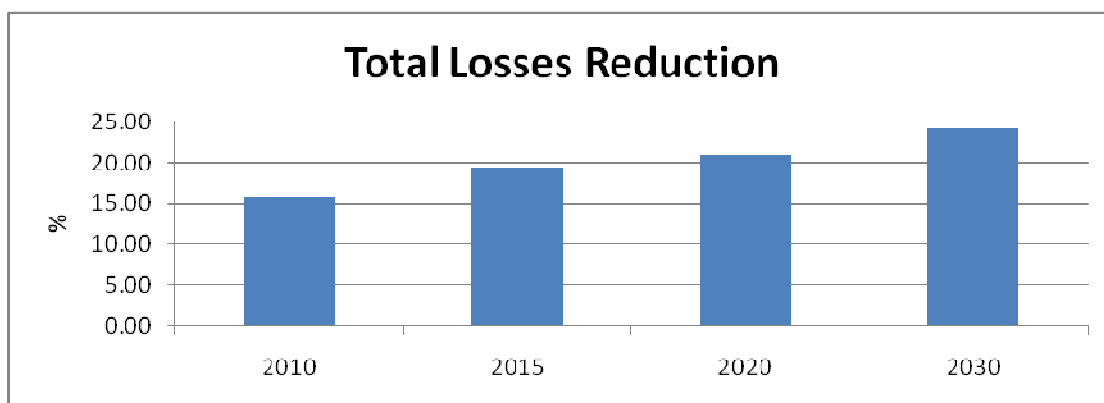


Figure 2.3. Total losses reduction after introduction of DG.

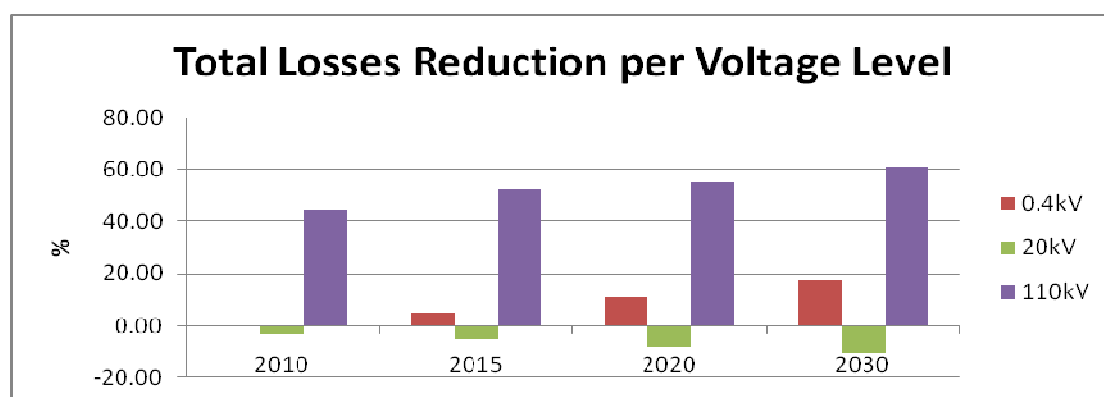


Figure 2.4. Losses reduction per voltage level after introduction of DG.

Figure 2.5 shows the reduction in transformer and circuit losses. It is evident that introduction of DG greatly reduces circuit losses as it reduces the power flows of the network. On the other hand, transformer losses are not affected significantly as the majority of transformer losses are no load losses.

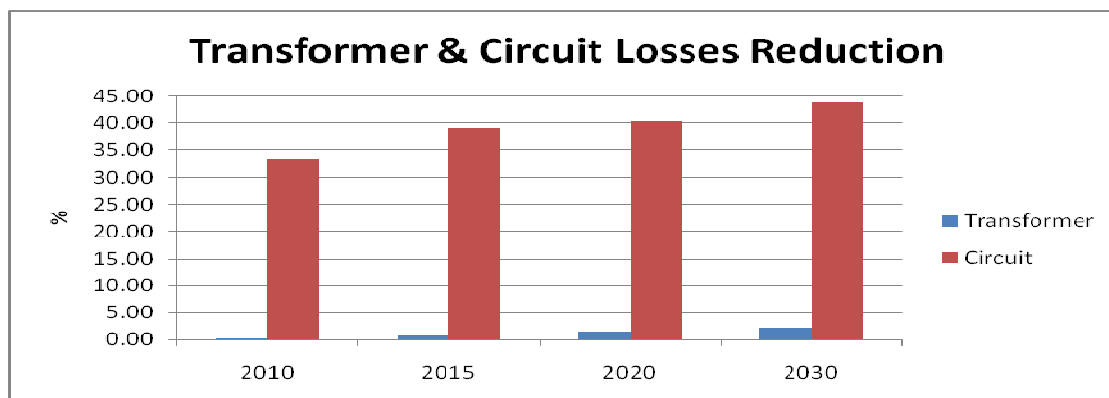


Figure 2.5. Reduction of transformer and circuit losses after introduction of DG.

Furthermore, Figure 2.6 presents a parametric analysis of avoided grams of CO<sub>2</sub> per kWh<sub>e</sub> of energy consumed annually coming from the marginal plant as a function of the emission factor (grams of CO<sub>2</sub> per kWh<sub>e</sub> produced) of the marginal plant thanks to losses reduction. Finally, Figure 2.7 quantifies the financial benefit of total losses reduction in €/MW<sub>peak</sub> assuming 3% inflation and 7% discount rate.

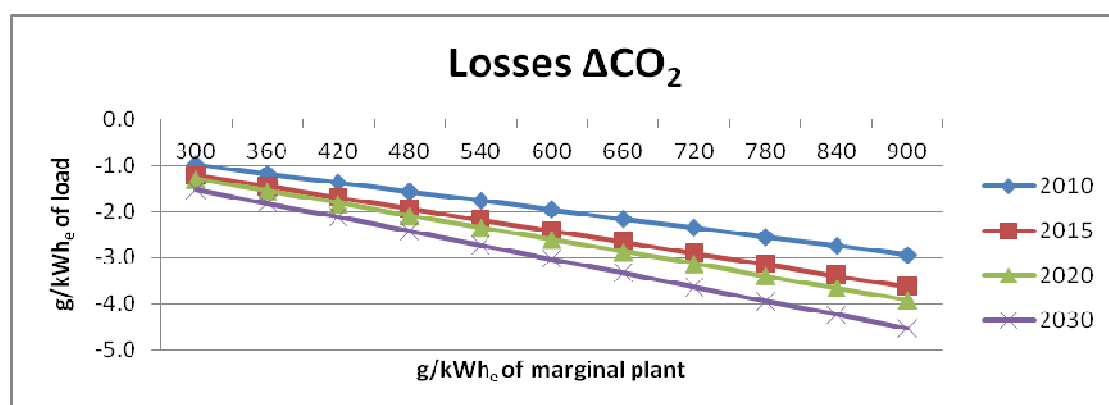


Figure 2.6. Environmental benefit from losses reduction.

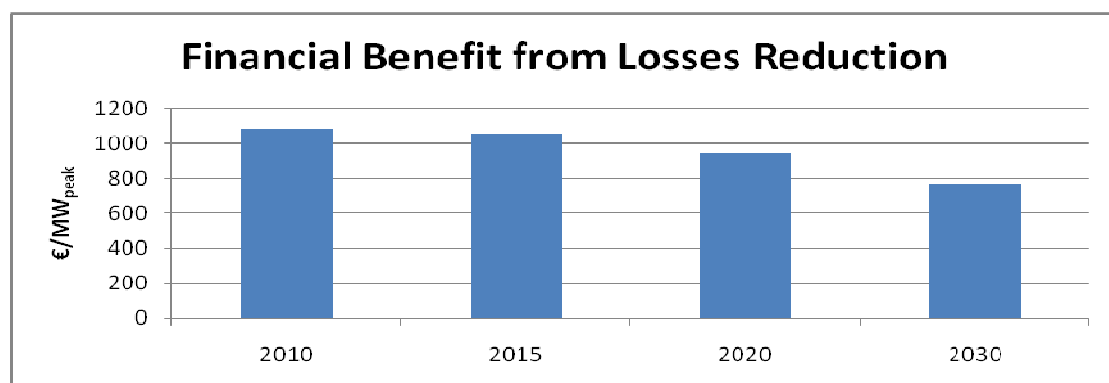


Figure 2.7. Financial benefit from losses reduction.

### 2.1.3 Reinforcement Requirements

The MVV Energie network operates within voltage and thermal limits for all DG penetration scenarios. On the other hand, reinforcement due to increased short circuit level is likely. For the purposes of this calculation, and in absence of any other information, it is assumed that all existing switchboards are rated at 16kA. Three headrooms are examined: 10%, 20% and 30%. Table 2.3 shows the short circuit capacity of the replacement switchboards, as supplied by MVV Energie.

Figure 2.8 presents the reinforcement requirements in terms of investment assuming 3% inflation and 7% discount rate. Apart from 2030 (10% headroom) where a 110kV switchboard needs to be replaced, the rest of the cases refer to replacement of 20kV switchboards. Reinforcement is presented in non cumulative fashion, assuming that investment taking place in one year is present when the following years are examined. For example, switchboards replaced in 2015 are assumed already replaced in 2020.

	New switchboard short circuit MVA
0.4 kV	17.3 (25 kA)
20 kV	750 (22 kA)
110 kV	5000 (26 kA)

Table 2.3. Short circuit MVA of new switchboards

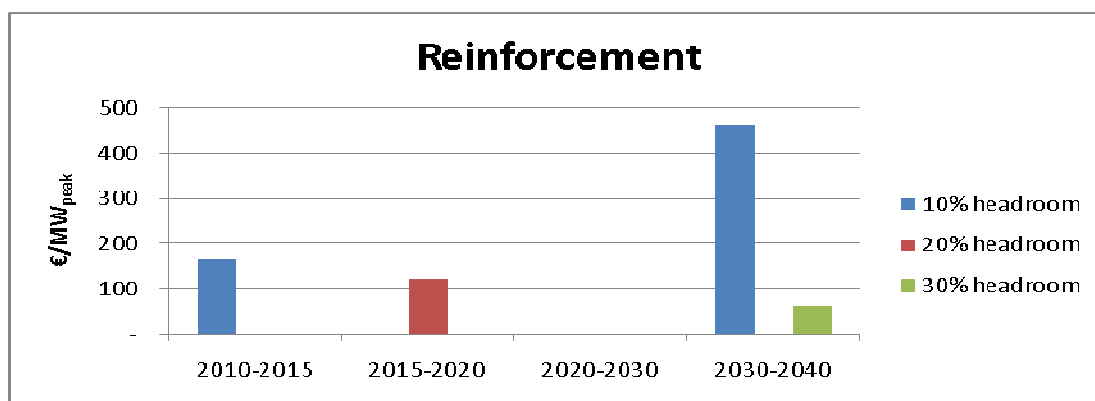


Figure 2.8. Reinforcement required due to increased short circuit levels.

### 2.1.4 Benefits Related to Local Power Generation

One of the most significant contributions of power generation using DG (RES and CHP) is reducing CO<sub>2</sub> emissions coming from central conventional marginal plant. Figure 2.9 to Figure 2.15 present a parametric analysis of avoided grams of CO<sub>2</sub> per kWh<sub>e</sub> of energy consumed annually coming from the marginal plant as a function of the emission factor

(grams of CO<sub>2</sub> per kW<sub>e</sub> produced) of the marginal plant thanks to power generation using DG. Figure 2.16 presents the total avoidance of CO<sub>2</sub> emissions thanks to power generation from DG. Finally, Figure 2.17 presents the total energy produced by local generation per kWh of demand.

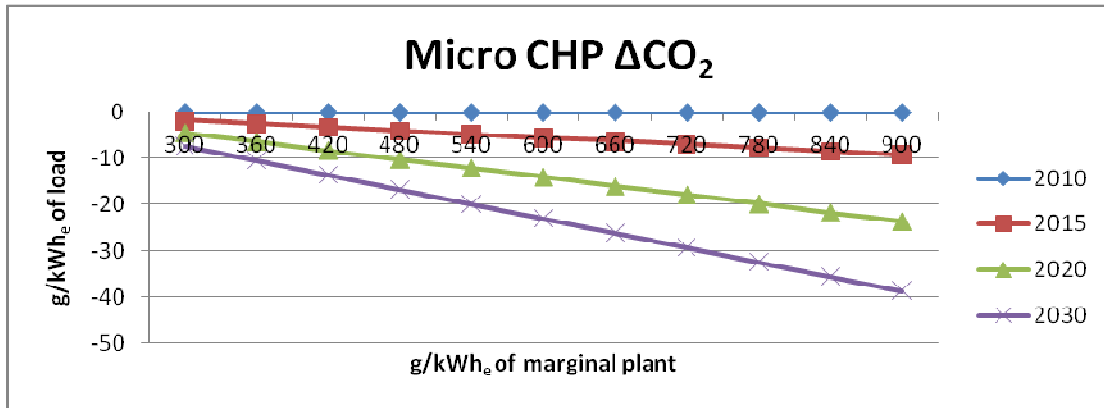


Figure 2.9. Parametric analysis of Micro CHP ΔCO<sub>2</sub>.

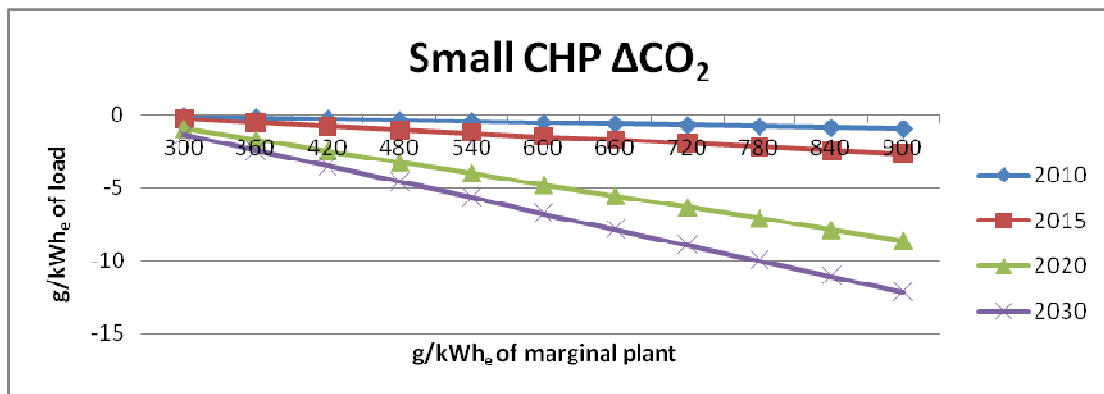


Figure 2.10. Parametric analysis of Small CHP ΔCO<sub>2</sub>.

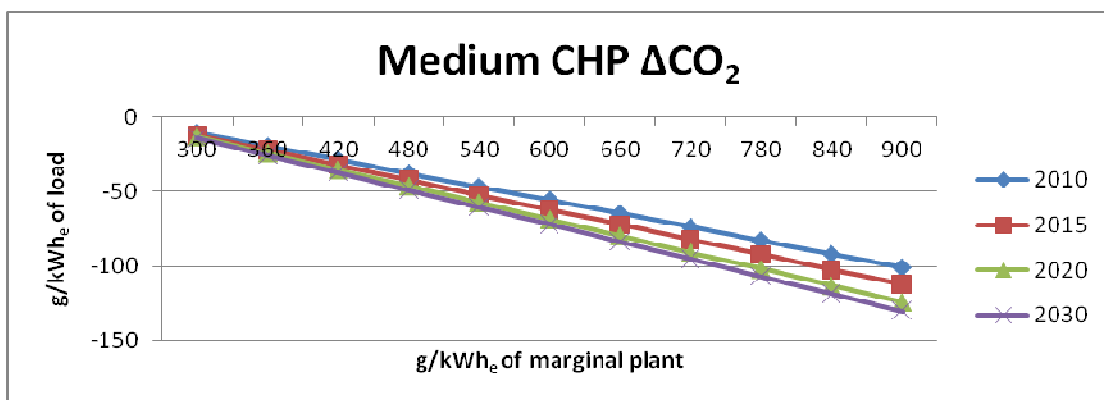


Figure 2.11. Parametric analysis of Medium CHP ΔCO<sub>2</sub>.

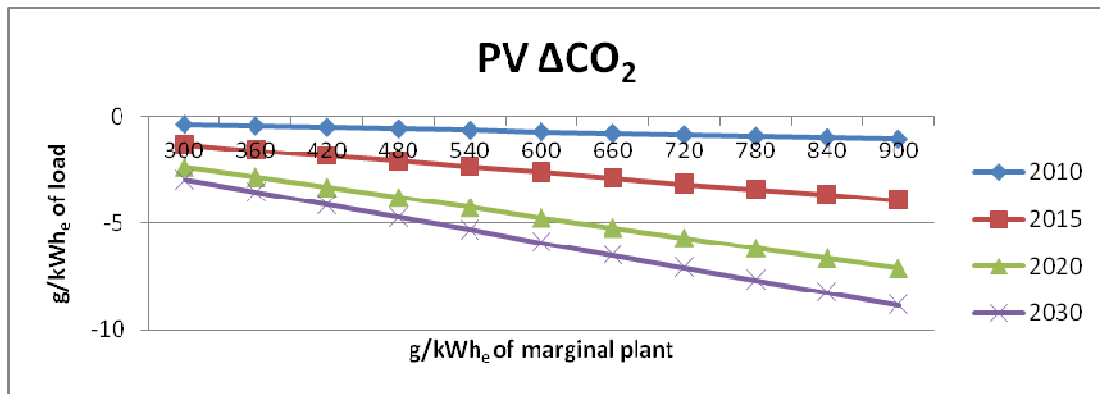


Figure 2.12. Parametric analysis of PV  $\Delta CO_2$ .

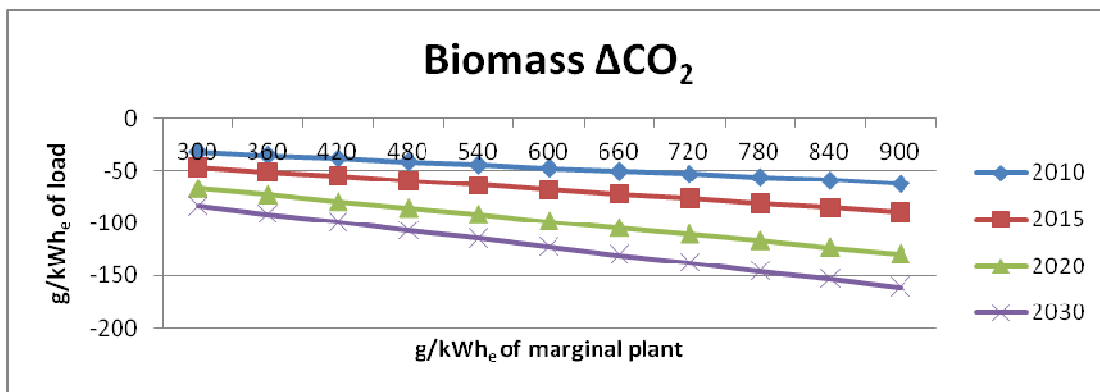


Figure 2.13. Parametric analysis of Biomass  $\Delta CO_2$ .

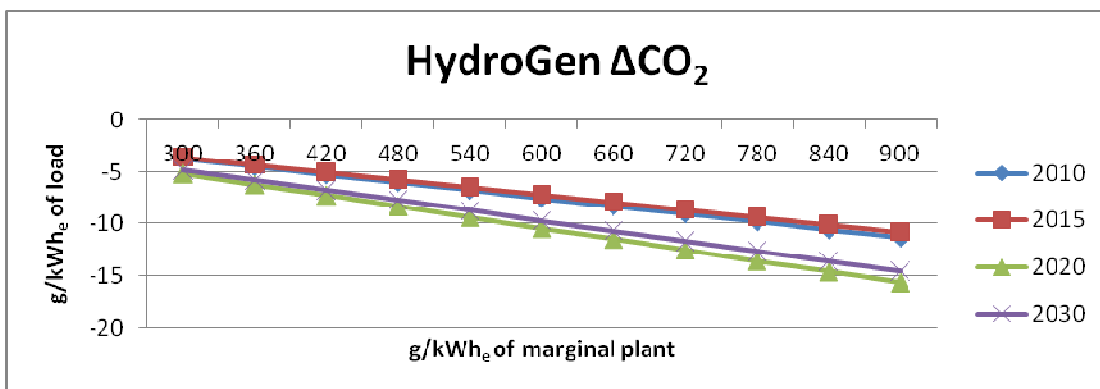


Figure 2.14. Parametric analysis of Hydro Generation  $\Delta CO_2$ .

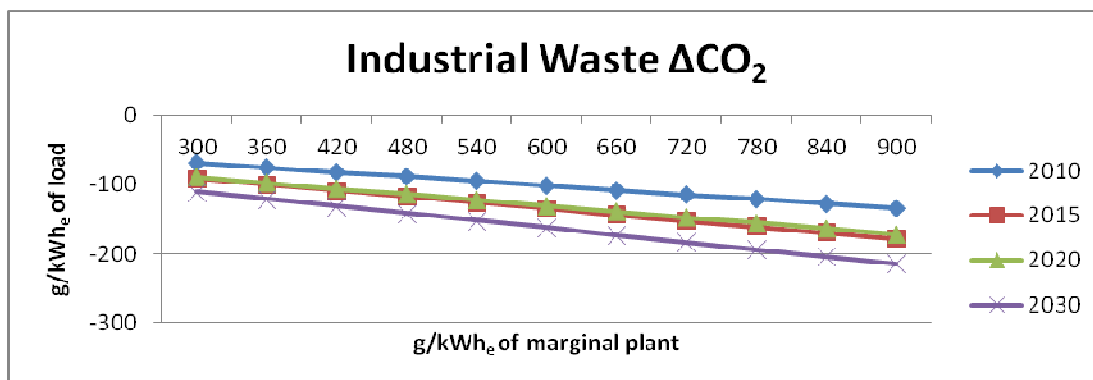


Figure 2.15. Parametric analysis of Industrial Waste  $\Delta\text{CO}_2$ .

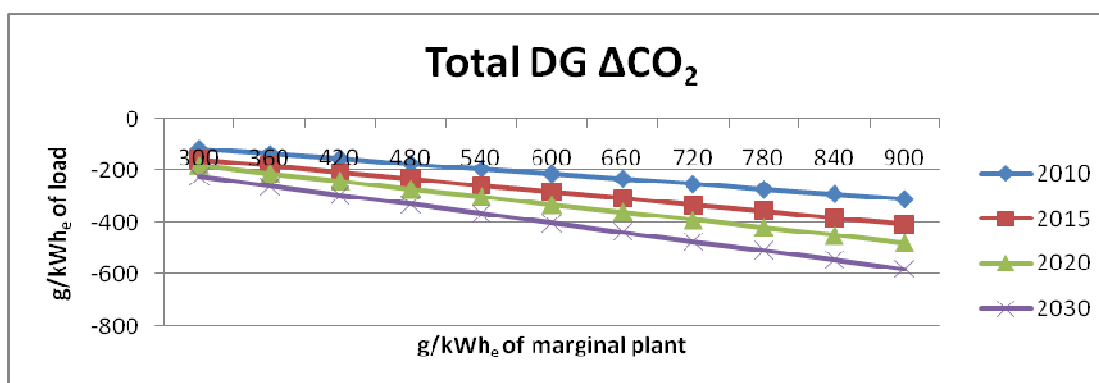


Figure 2.16. Parametric analysis of Total DG  $\Delta\text{CO}_2$ .

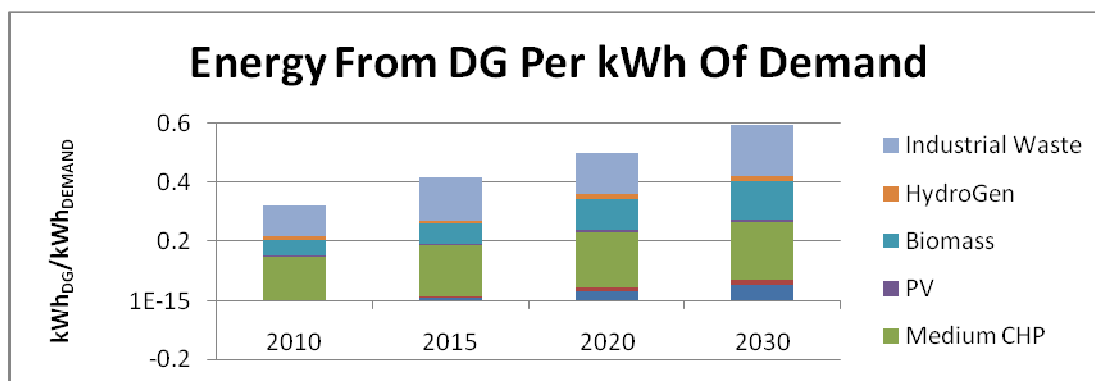


Figure 2.17. Energy from DG per kWh of demand.

### 2.1.5 Total Environmental Benefit

Figure 2.18 presents the total avoided CO<sub>2</sub> emission from DG, coming from both power generation (RES and CHP) and losses reduction. It has to be noted that the majority of

benefit is coming from power generation, with reduction of losses having only a small contribution in the total CO<sub>2</sub> emissions reduction (<1%).

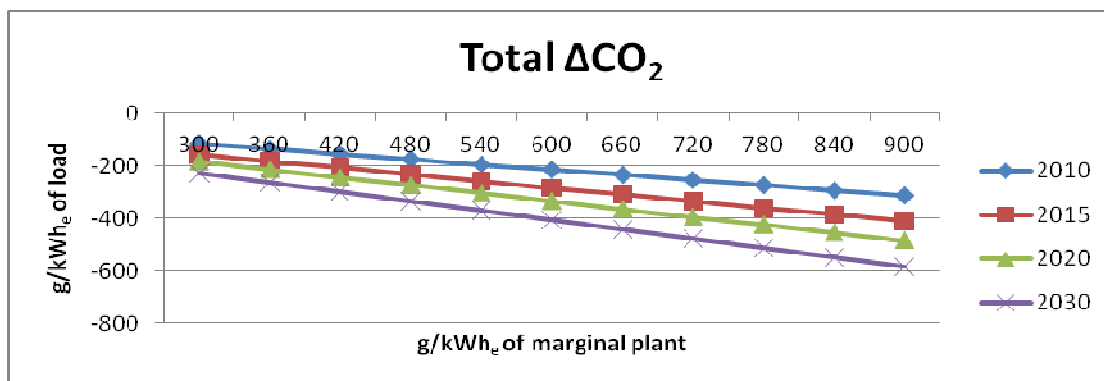


Figure 2.18. Parametric analysis of Total ΔCO<sub>2</sub>.

### 2.1.6 Benefits Related to Total Network Cost

The total network cost reduction for each of the examined time windows is presented in Figure 2.19. Two costs are taken into consideration: cost of equipment because of the need for network reinforcement and cost of losses reduction. The results are presented in €/MW<sub>peak</sub>. It can be seen that penetration of DG is financially beneficial as, although DG requires network reinforcement, the reduction in losses compensates the cost of investment and brings financial benefit.

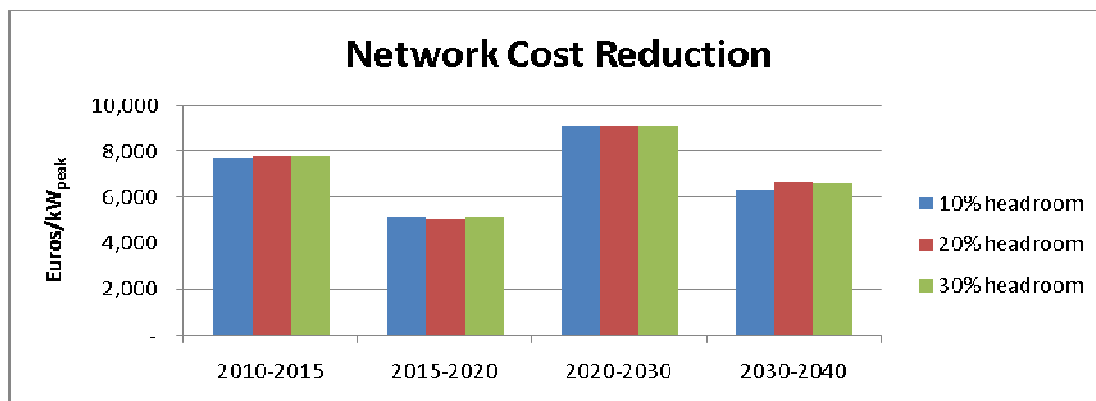


Figure 2.19. Network cost reduction.

### 2.1.7 Benefits Related to GSP Power Flows

Figure 2.20 presents the maximum GSP power flows with and without DG. In the absence of DG, the maximum GSP power flow is steadily increasing. On the other hand,

the maximum GSP power flow is slightly decreasing in the presence of DG. Figure 2.21 to Figure 2.24 show the GSP power flow for a winter Saturday, with and without DG for 2010, 2015, 2020 and 2030.

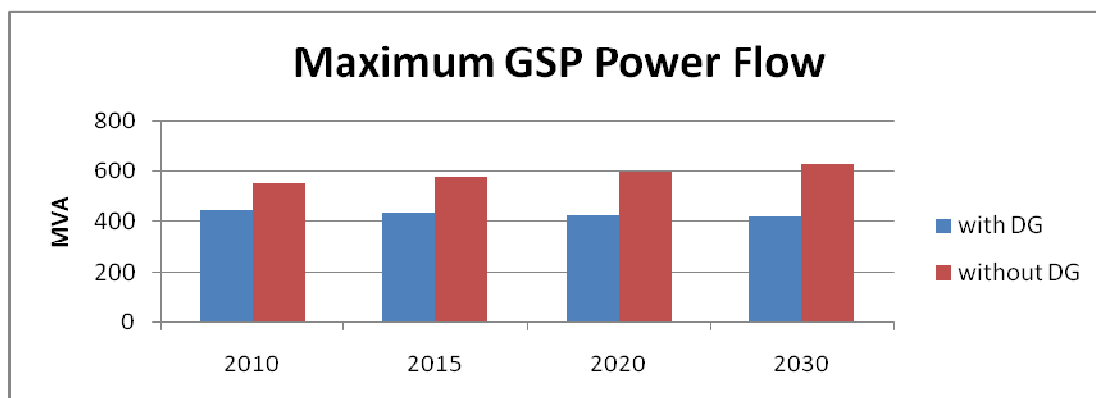


Figure 2.20. Maximum GSP power flow.

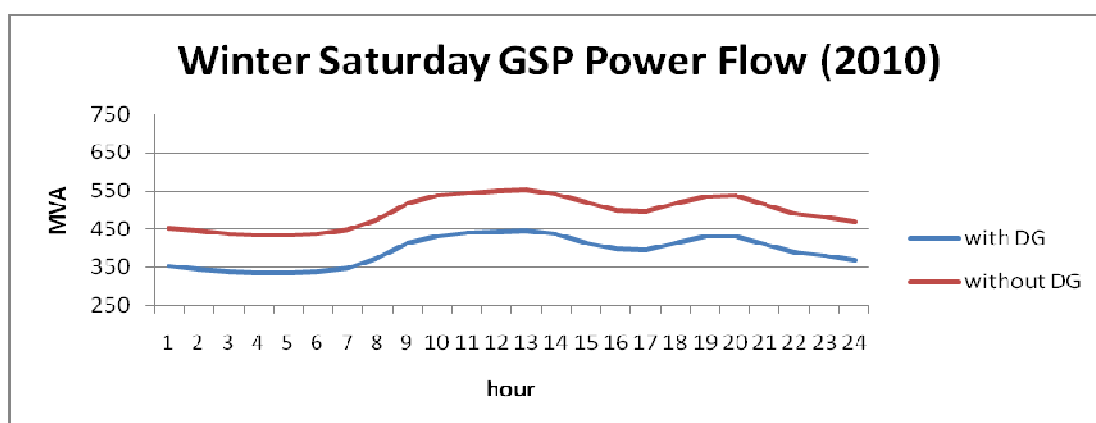


Figure 2.21. Winter Saturday GSP power flow (2010).

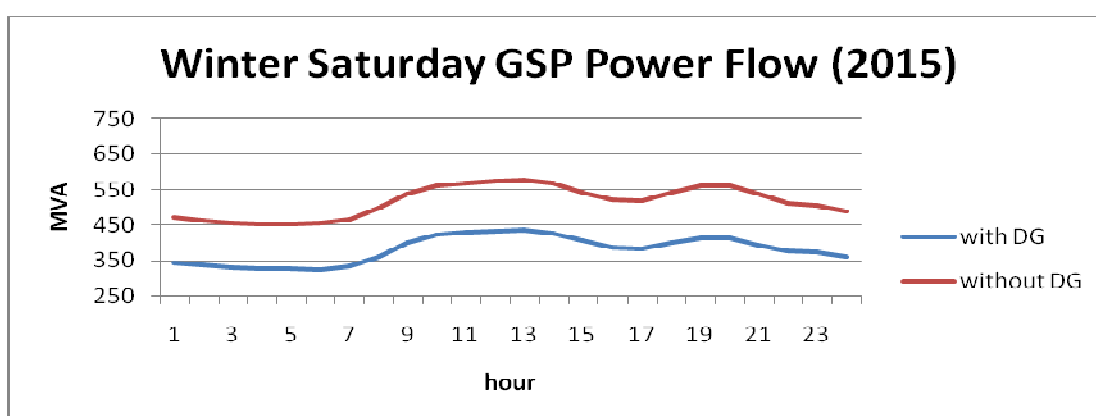


Figure 2.22. Winter Saturday GSP power flow (2015).

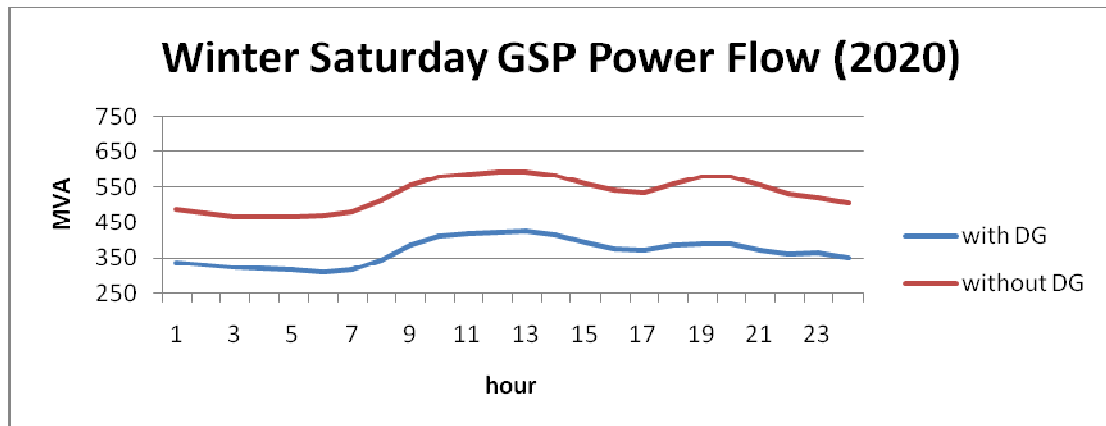


Figure 2.23. Winter Saturday GSP power flow (2020).

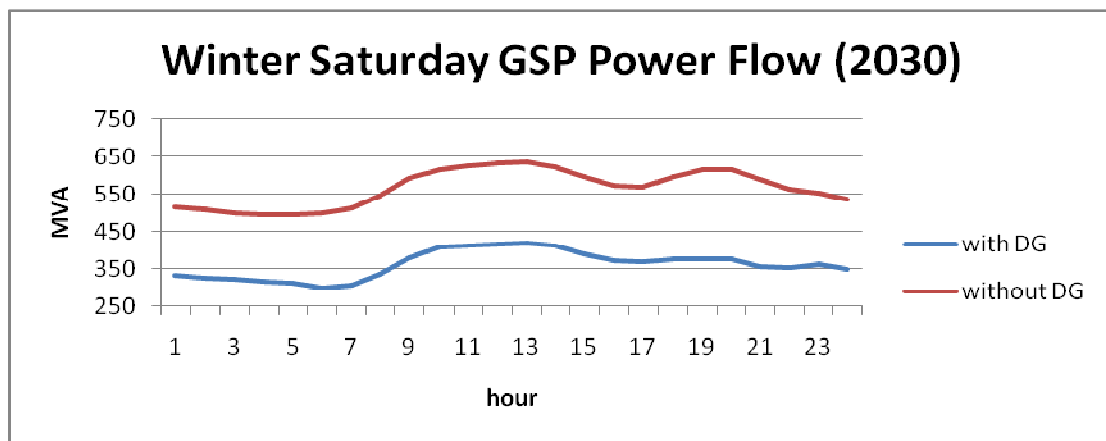


Figure 2.24. Winter Saturday GSP power flow (2030).

### 2.1.8 Conclusion

The German network is a **strong network** with low losses and able to accommodate the envisaged DG penetration evolution **without thermal and voltage problems**. On the other hand, depending on the short circuit capacity headroom available in the existing switchgear, **reinforcement due to increased short circuit levels** is likely.

**Losses decrease with the installation of DG** and reduction in losses increases in the future as DG penetration increases much faster than load. It is noted that circuit losses decrease dramatically compared to transformer losses.

In terms of CO<sub>2</sub> emissions, the reduction in network losses in combination with local power generation from CHP and RES results in **significant reduction in CO<sub>2</sub> emissions** thanks to avoided emissions from the marginal plant of the system.

Overall, **network cost decreases** thank to losses reduction, although increased DG penetration is likely to require switchgear reinforcement because of increased short circuit levels.

Finally, **DG penetration decreases the maximum GSP power flows** with potential benefits coming from deferral of transmission system investments.

## 2.2 MicroGrid Scenarios

### 2.2.1 General Information

The same MVV Energie network was used to examine the impact of micro DG. For this, the 2010 maximum load per voltage level was considered to be the base load and two LV load growth cases were examined: +10% and +50% of the 2010 LV load. In terms of micro DG penetration, four cases were considered: 0%, 50%, 100% and 150% of the 2010 LV load. Figure 2.25 shows the LV load growth scenarios and Figure 2.26 shows the micro DG penetration scenarios. In all cases, the load in the rest of the voltage levels was considered fixed and equal to the one in the 2010 case. Only Micro CHP and PV were considered as micro DGs, with 60% and 40% share of the total micro DG capacity, respectively.

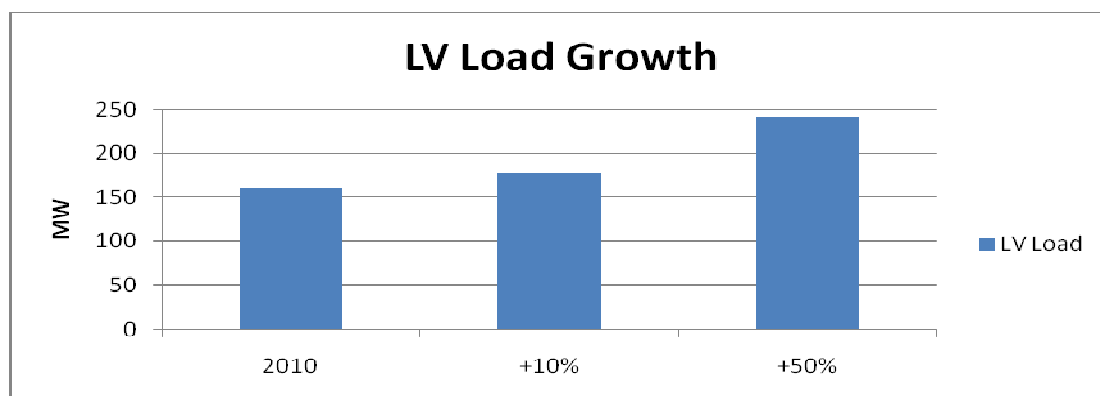


Figure 2.25. LV load growth scenarios.

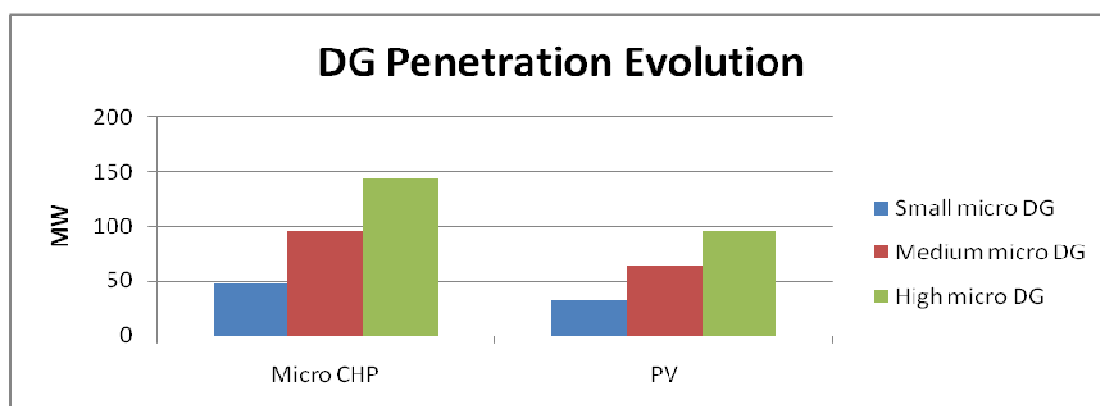


Figure 2.26. Micro DG penetration evolution scenarios.

### 2.2.2 Benefits Related to Losses

Figure 2.27 shows the total reduction in network losses after the introduction of micro DG. As micro DG penetration increases the losses reduction increases. Figure 2.28 presents the total losses reduction per voltage level after the introduction of micro DG. It is noted that losses reduce at all voltage levels.

Figure 2.29 shows the reduction in transformer and circuit losses. It is obvious that the benefit of micro DG mainly comes from the reduction of circuit losses. Transformer losses also decrease but not as profoundly as circuit losses.

Figure 2.30 and Figure 2.31 present a parametric analysis of avoided grams of CO<sub>2</sub> per kWh<sub>e</sub> of energy consumed annually coming from the marginal plant as a function of the emission factor of the marginal plant. Figure 2.32 quantifies the financial benefit of total losses reduction in €/MW<sub>peak</sub>.

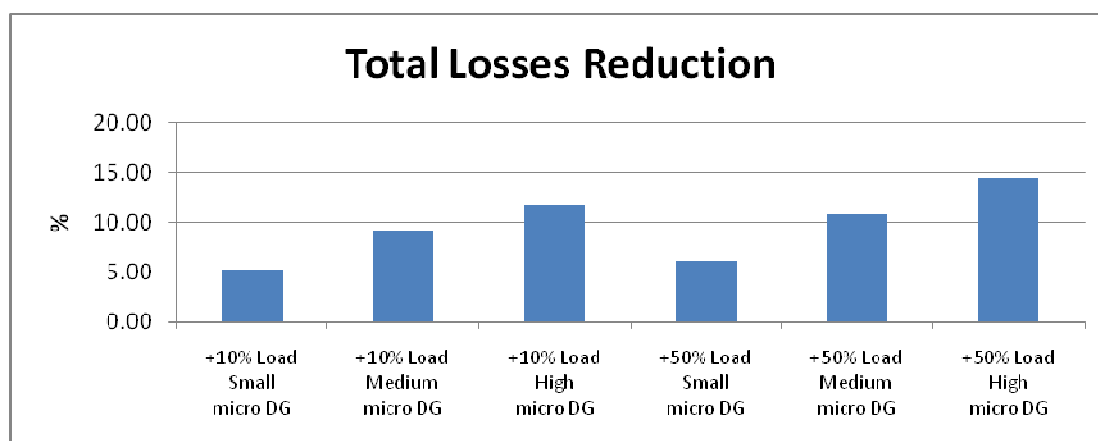


Figure 2.27. Total losses reduction after introduction of micro DG.

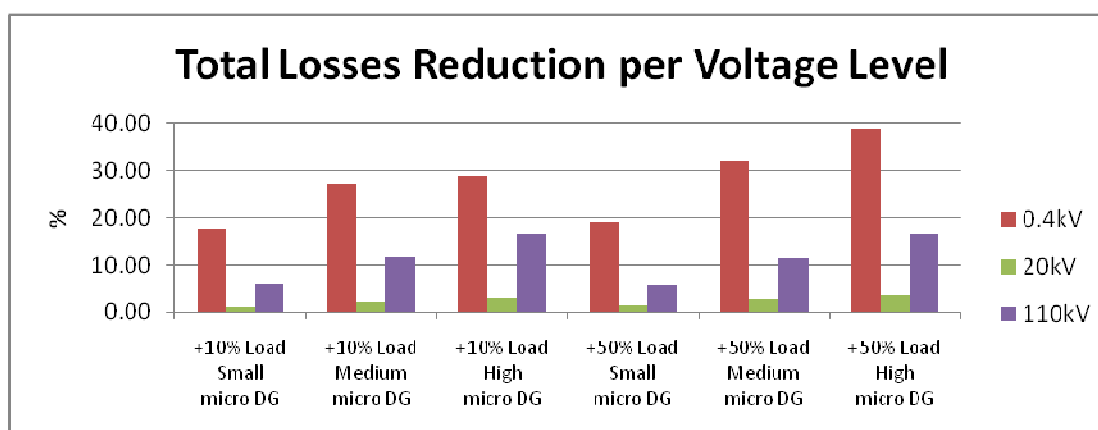


Figure 2.28. Losses reduction per voltage level after introduction of DG.

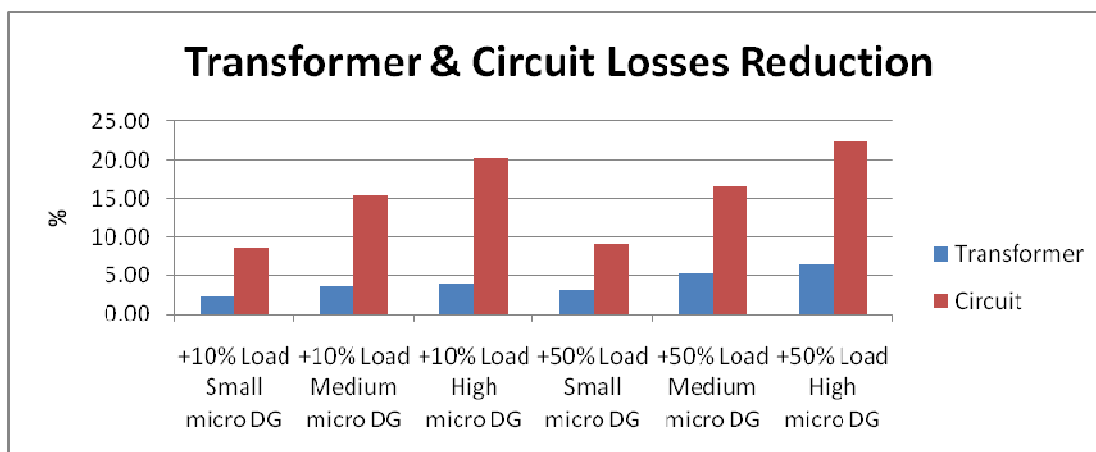


Figure 2.29. Total circuit and transformer losses / demand with micro DG.

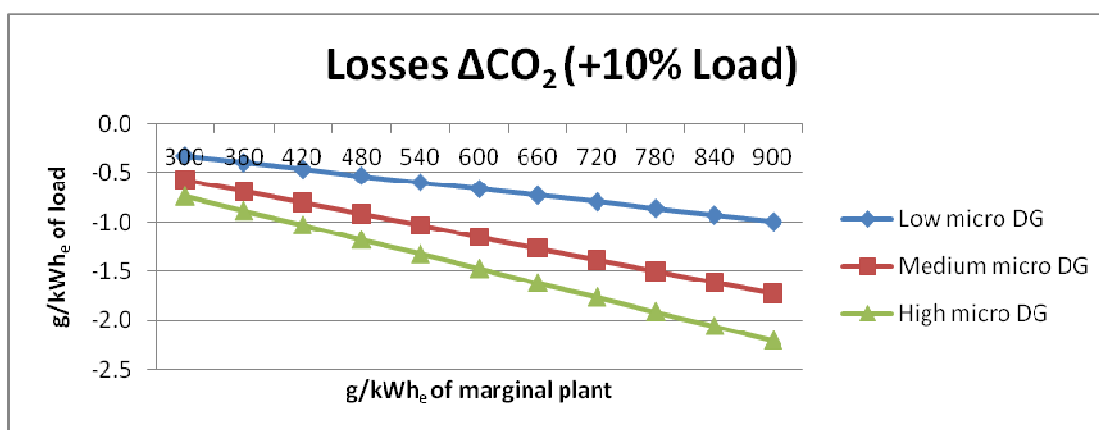


Figure 2.30. Environmental benefit from losses reduction (+10% load).

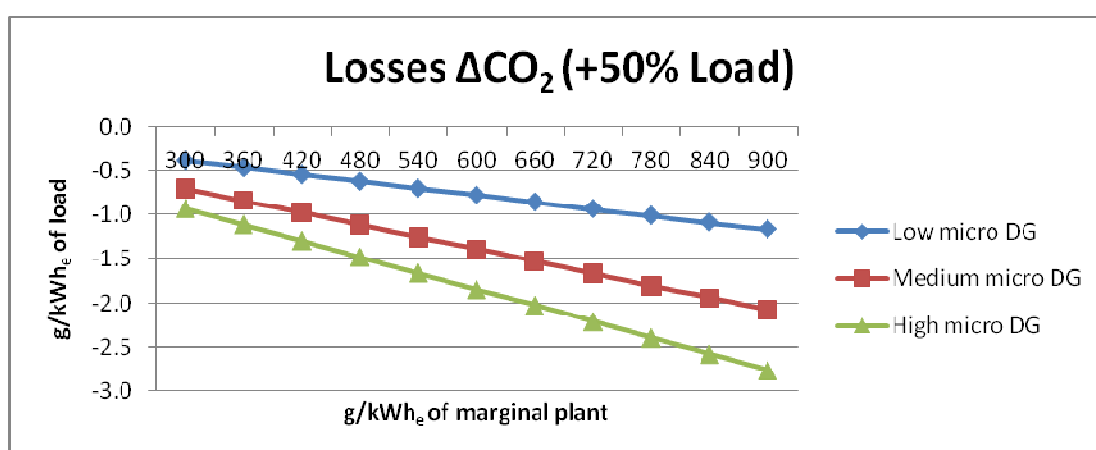


Figure 2.31. Environmental benefit from losses reduction (+50% load).

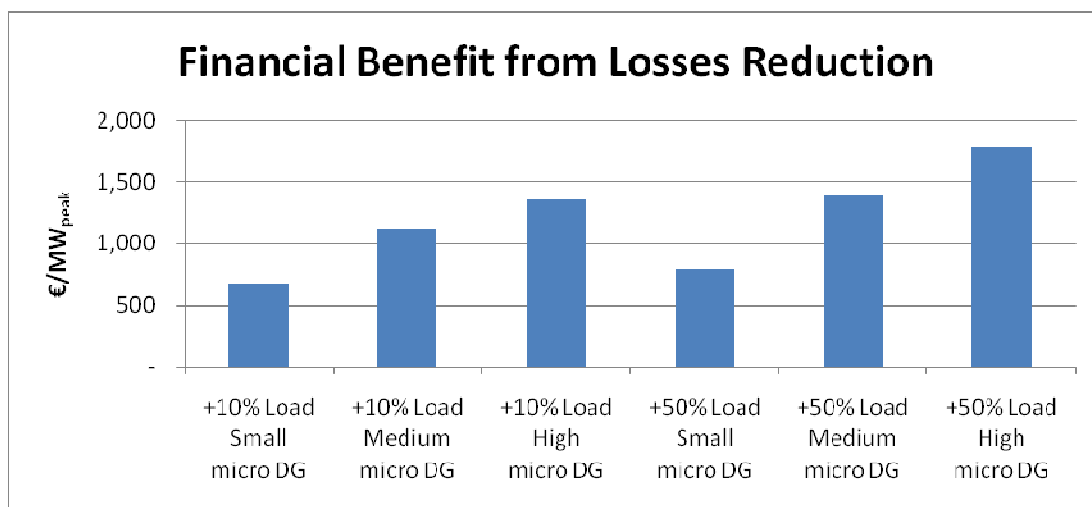


Figure 2.32. Financial benefit from losses reduction.

### 2.2.3 Reinforcement Requirements

The network operates within voltage and thermal limits for all micro DG penetration scenarios. On the other hand, reinforcement due to increased short circuit level is likely. As in the previous case, it is assumed that all existing switchboards are rated at 16kA. Three headrooms are examined: 10%, 20% and 30%.

Figure 2.33 presents the reinforcement requirements in terms of investment in €/MW<sub>peak</sub>. Obviously, as only micro DG is taken into consideration, reinforcement due to increased short circuit levels is only required at 0.4kV. In addition, it is noted that reinforcement is required only when 10% headroom is available at the switchgear.

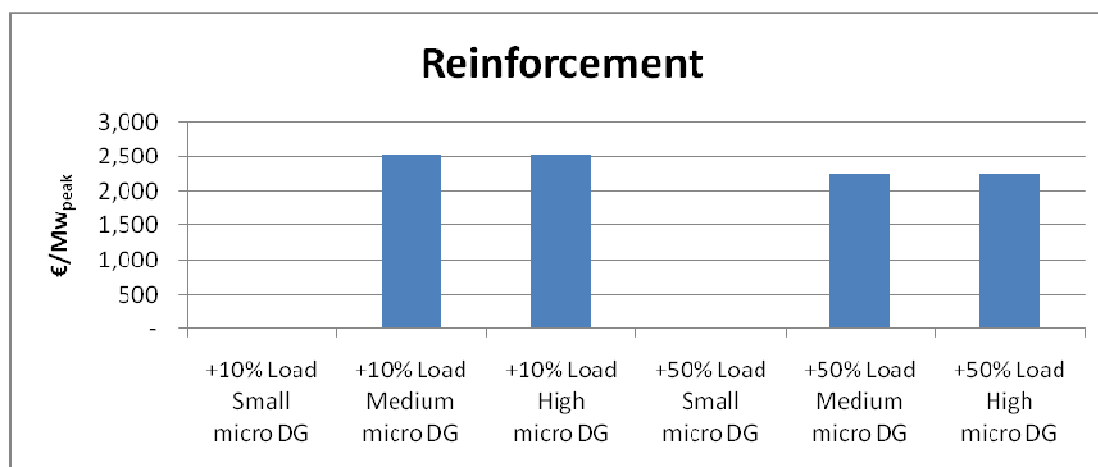


Figure 2.33. Reinforcement required due to increased short circuit levels.

### 2.2.4 Benefits Related to Local Power Generation

Figure 2.34 to Figure 2.37 present a parametric analysis of avoided grams of CO<sub>2</sub> per kWh<sub>e</sub> of energy consumed annually coming from the marginal plant as a function of the emission factor (grams of CO<sub>2</sub> per kWh<sub>e</sub> produced) of the marginal plant thanks to power generation using micro DGs (Micro CHP and PV). Figure 2.38 and Figure 2.39 present the total avoidance of CO<sub>2</sub> emissions thanks to power generation from micro DG. Finally, Figure 2.40 and Figure 2.41 present the total energy produced by local generation per kWh of demand for 10% and 50% load increase, respectively.

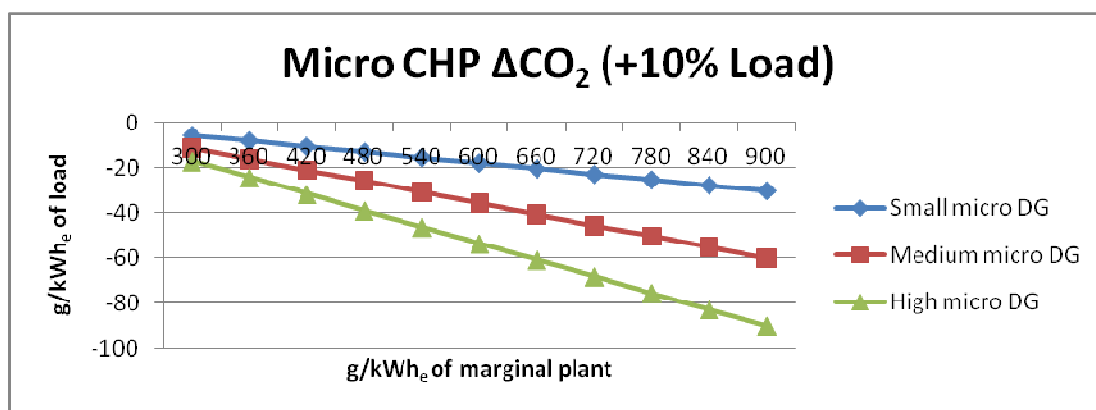


Figure 2.34. Parametric analysis of Micro CHP ΔCO<sub>2</sub> (+10% load).

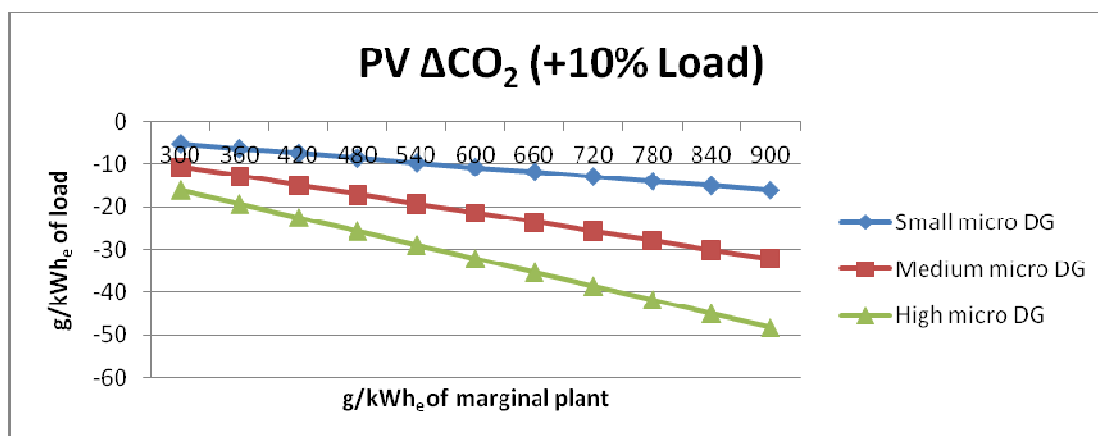


Figure 2.35. Parametric analysis of PV ΔCO<sub>2</sub> (+10% load).

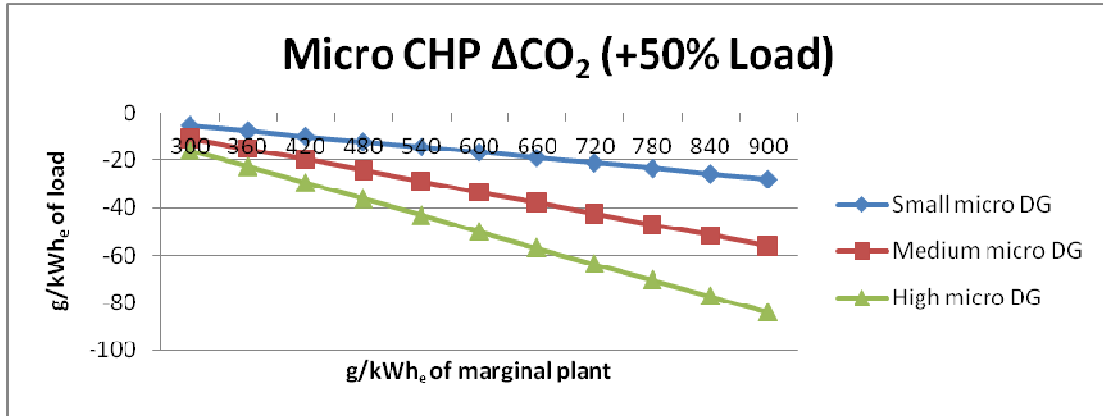


Figure 2.36. Parametric analysis of Micro CHP  $\Delta\text{CO}_2$  (+50% load).

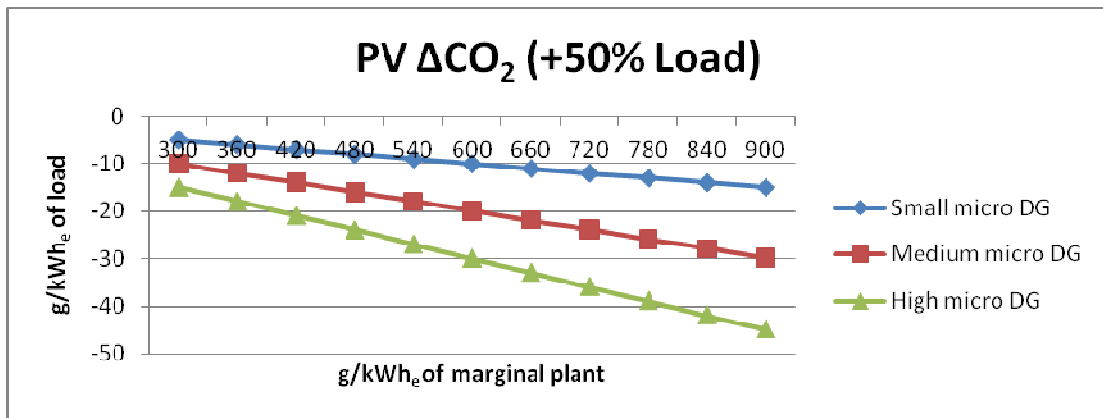


Figure 2.37. Parametric analysis of PV  $\Delta\text{CO}_2$  (+50% load).

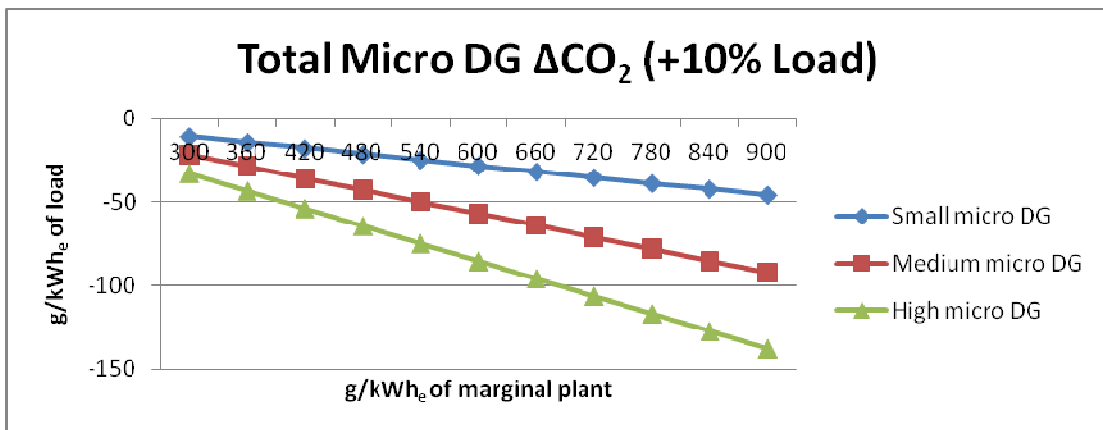


Figure 2.38. Parametric analysis of total micro DG  $\Delta\text{CO}_2$  (+10% load).

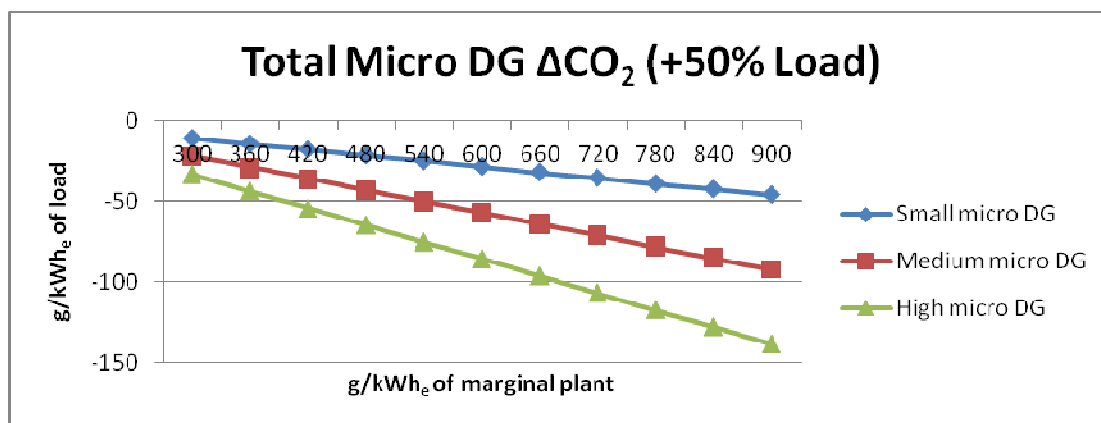


Figure 2.39. Parametric analysis of total micro DG ΔCO<sub>2</sub> (+50% load).

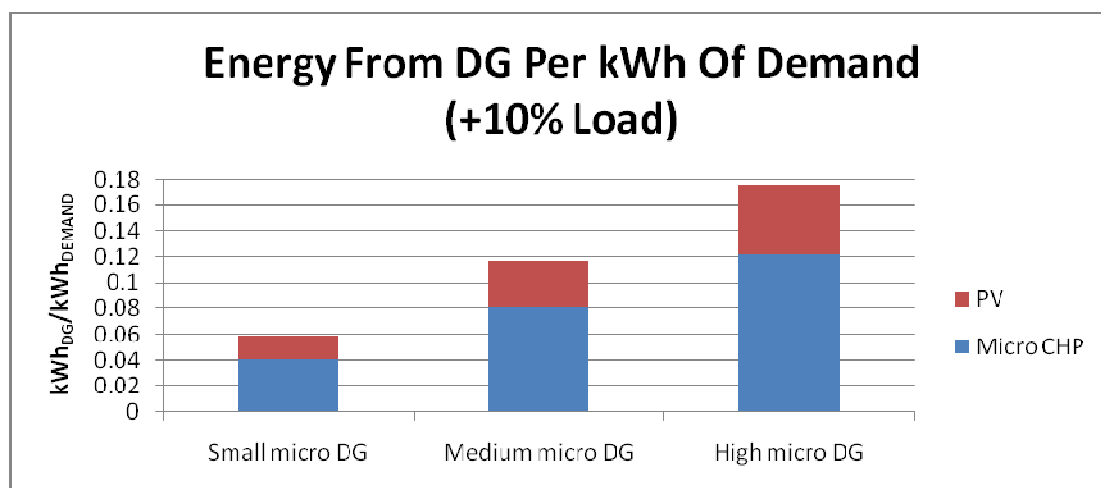


Figure 2.40. Energy from micro DG per kWh of demand (+10% load).

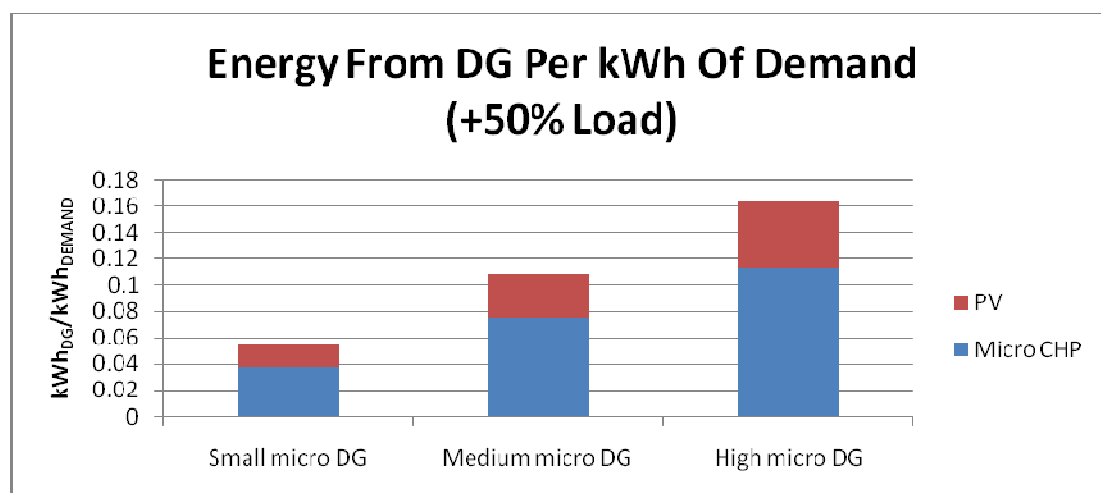


Figure 2.41. Energy from micro DG per kWh of demand (+50% load).

### 2.2.5 Total Environmental Benefit

Figure 2.42 and Figure 2.43 present the total avoided CO<sub>2</sub> emission from micro DG, coming from both power generation (Micro CHP and PV) and losses reduction. It has to be noted that the majority of benefit is coming from power generation, with reduction of losses having only a small contribution in the total CO<sub>2</sub> emissions reduction.

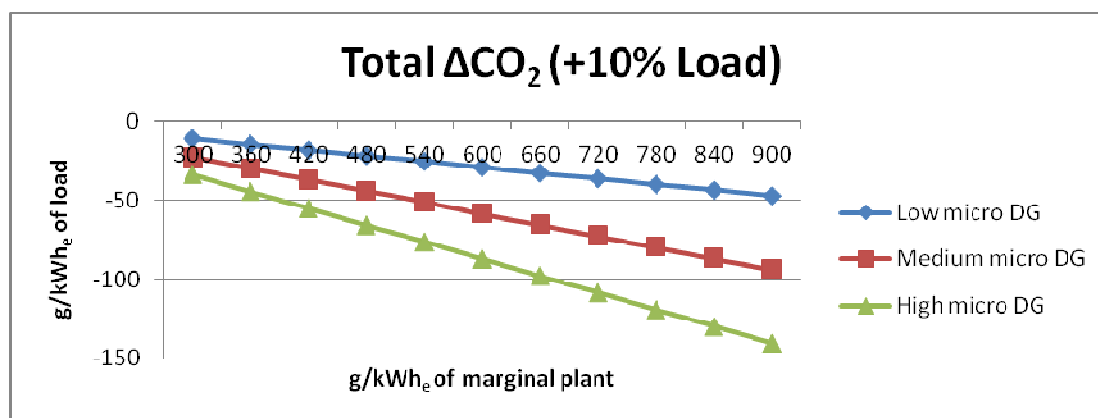


Figure 2.42. Parametric analysis of Total ΔCO<sub>2</sub> (+10% load).

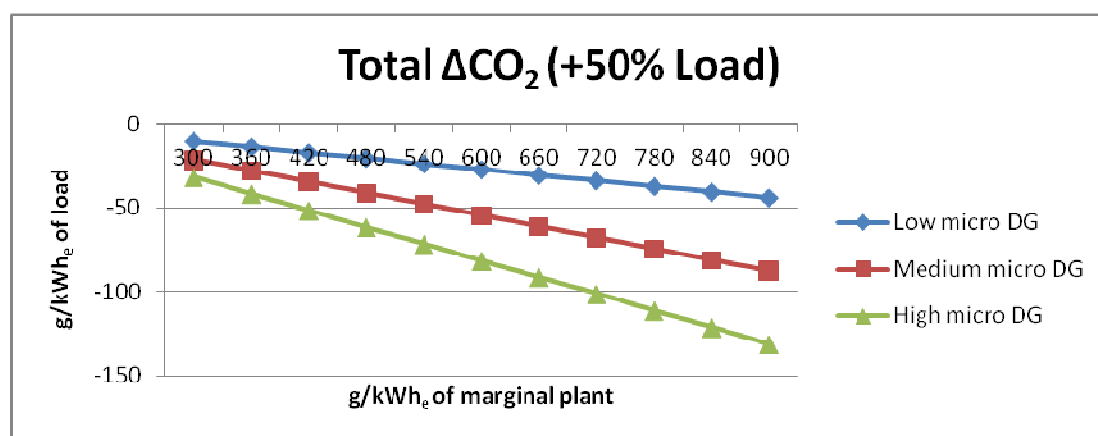


Figure 2.43. Parametric analysis of Total ΔCO<sub>2</sub> (+50% load)

### 2.2.6 Benefits Related to Total Network Cost

The total network cost reduction per case is presented in Figure 2.44. The introduction of micro DG is financially beneficial as the financial benefit from losses reduction is higher than the required network reinforcement.

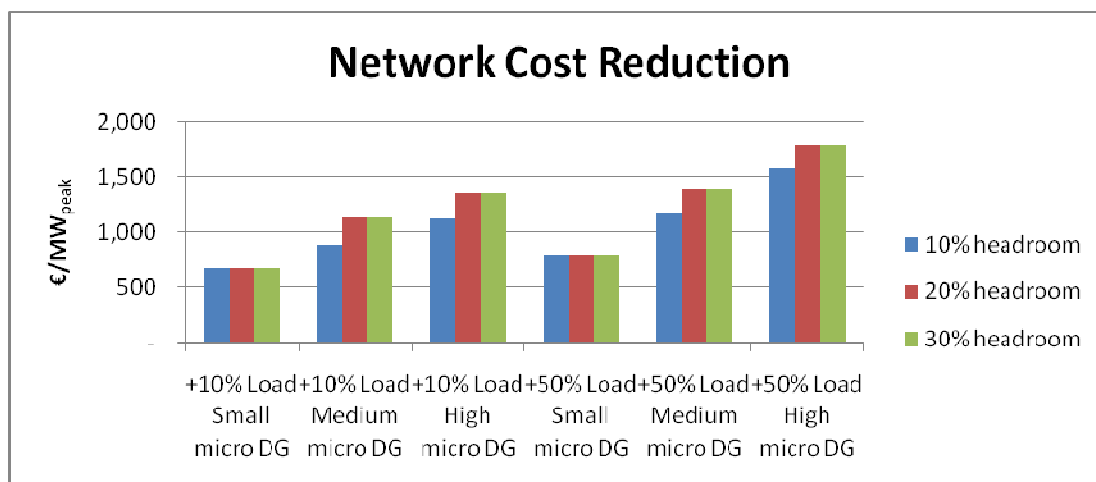


Figure 2.44. Network cost reduction.

### 2.2.7 Benefits Related to GSP Power Flows

Figure 2.45 presents the maximum GSP power flows with and without micro DG. The maximum GSP power flow is steadily decreasing with increasing micro DG penetration. Figure 2.46 and Figure 2.47 show the GSP power flow for a winter weekday, with and without micro DG. It is noted that micro DG, apart from reducing the maximum GSP power flow, change the time of peak occurrence.

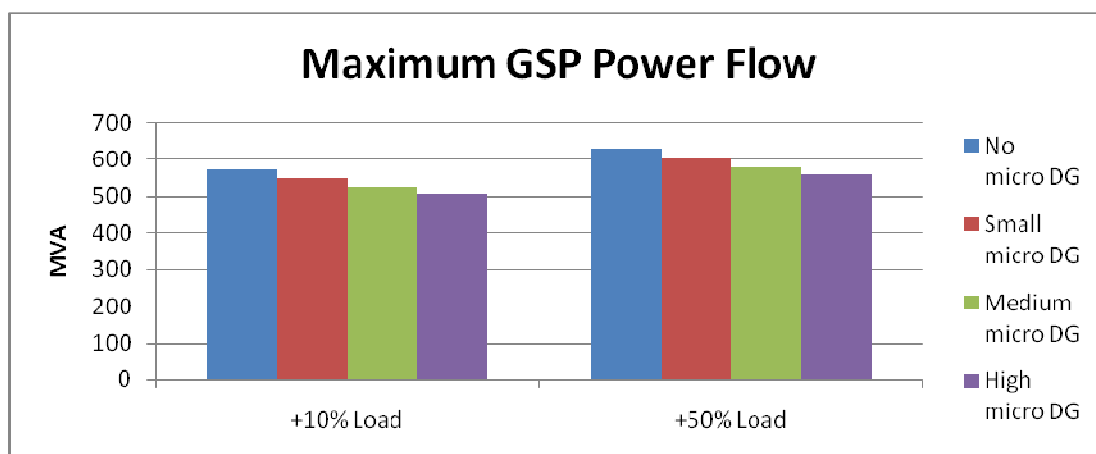


Figure 2.45. Maximum GSP power flow.

### 2.2.8 Conclusion

The German network is a **strong network** with low losses and able to accommodate the envisaged micro DG penetration **without thermal and voltage problems**. On the other

hand, depending on the short circuit capacity headroom available in the existing 0.4kV switchgear, **reinforcement due to increased short circuit levels** is likely.

**Losses decrease with increasing micro DG penetration.** It is noted that circuit losses decrease dramatically compared to transformer losses.

In terms of CO<sub>2</sub> emissions, the reduction in network losses in combination with local power generation from Micro CHP and PV results in **significant reduction in CO<sub>2</sub> emissions** thanks to avoided emissions from the marginal plant of the system.

Overall, **network cost decreases** thank to losses reduction, although increased micro DG penetration is likely to require switchgear reinforcement because of increased short circuit levels.

Finally, micro DG penetration **decreases the maximum GSP power flows and even changes the time of peak occurrence** with potential benefits coming from deferral of transmission system investments.

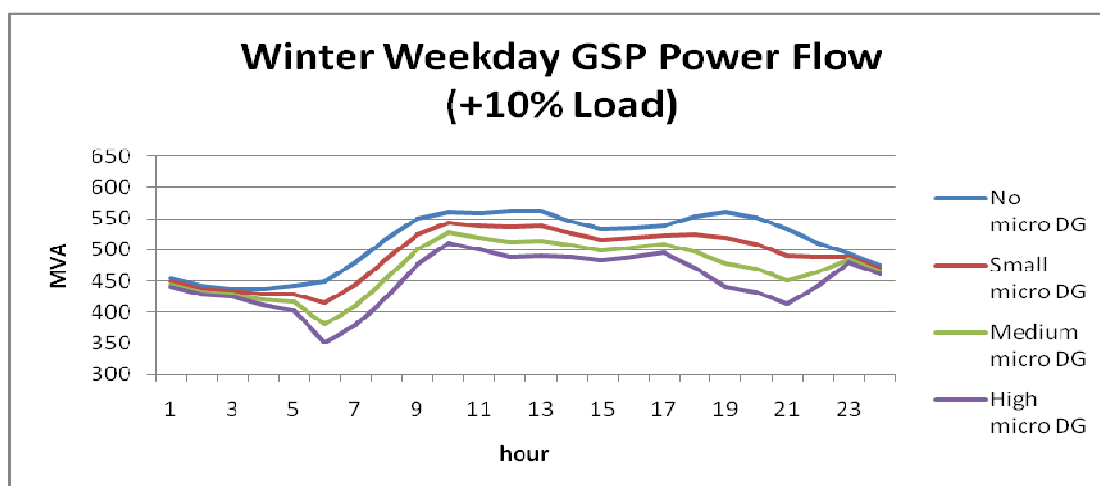


Figure 2.46. Winter weekday GSP power flow (+10% load).

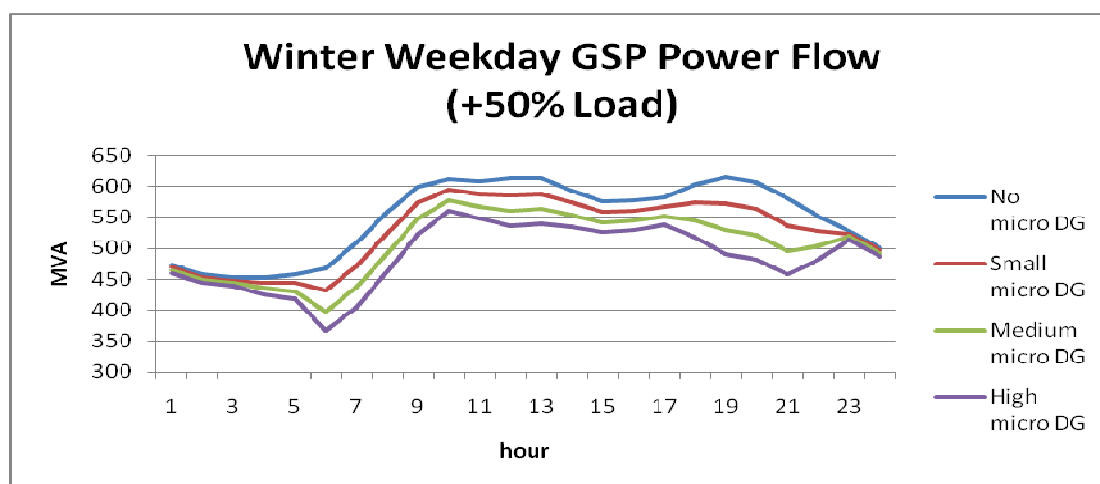


Figure 2.47. Winter weekday GSP power flow (+50% load).

### 3. Distribution Network Analysis for Poland

#### 3.1 Polish Scenarios

##### 3.1.1 General Information

The Polish distribution network we have worked with has three voltage levels (0.4kV, 15kV and 110kV) and is characterized by many long overhead lines at 15kV and very large transformer installed capacity. Basic information regarding the structure of the network is given on Table 3.1. The composition of the load is given on Table 3.2.

Voltage level	0.4kV	15kV	110kV
<b>Number of different module types</b>	6	4	1
<b>Number of each module type per GSP</b>	Module type 1: 443	Module type 1: 2	1
	Module type 2: 782	Module type 2: 4	
	Module type 3: 329	Module type 3: 2	
	Module type 4: 249	Module type 4: 4	
	Module type 5: 389		
	Module type 6: 242		
<b>Total number of modules per GSP</b>	2434	12	1
<b>Number of feeders per module type</b>	Module type 1: 2	Module type 1: 21	7
	Module type 2: 2	Module type 2: 11	
	Module type 3: 2	Module type 3: 15	
	Module type 4: 3	Module type 4: 10	
	Module type 5: 3		
	Module type 6: 5		
<b>Total number of feeders</b>	6232	156	7
<b>Total number of transformers</b>	2434	12*2=24	1*2=2
<b>Capacity of transformers per module type (in MVA)</b>	Module type 1: 0.04	Module type 1: 25*2=50	160*2=320
	Module type 2: 0.063	Module type 2: 16*2=32	
	Module type 3: 0.1	Module type 3: 16*2=32	
	Module type 4: 0.16	Module type 4: 25*2=50	
	Module type 5: 0.25		
	Module type 6: 0.63		

Table 3.1. Structure of the Polish distribution network

According to the data we have received from our partners, the peak load is 195MW and its annual increase rate is 5.15% from 2010 to 2020 and 2% from 2020 to 2040; on the other hand, the expected DG capacity per voltage level in each of the years 2010, 2015, 2020 and 2030 is given on Figure 3.1 to Figure 3.4. We can see that a very large

penetration of onshore wind turbines at 15kV and 110kV voltage levels is expected, followed by a significant penetration of landfill gas and biomass plants at 15kV; micro DG (DG at the low voltage level) is expected to get installed after 2020 and it will include biomass, hydro, PV, onshore wind and CHP technologies.

	0.4kV	15kV	110kV
Residential with electrical heating	32,76%	0%	0%
Residential without electrical heating	3,64%	0%	0%
Industrial	0%	29,28%	0%
Commercial	8,32%	14,40%	0%
Agricultural	7,28%	4,32%	0%
<b>Total</b>	<b>52%</b>	<b>48%</b>	<b>0%</b>

Table 3.2. Load composition of the Polish distribution network.

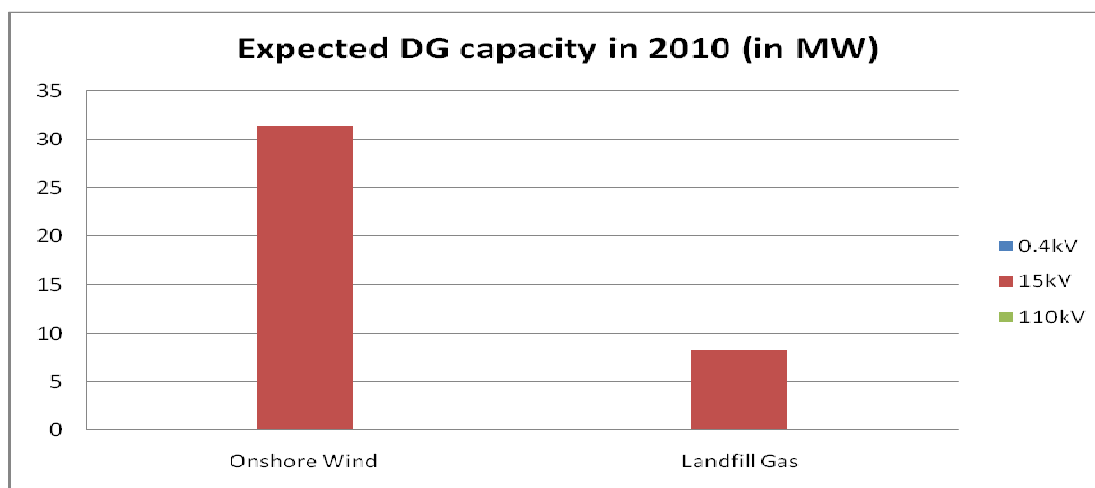


Figure 3.1. Expected DG capacity in 2010.

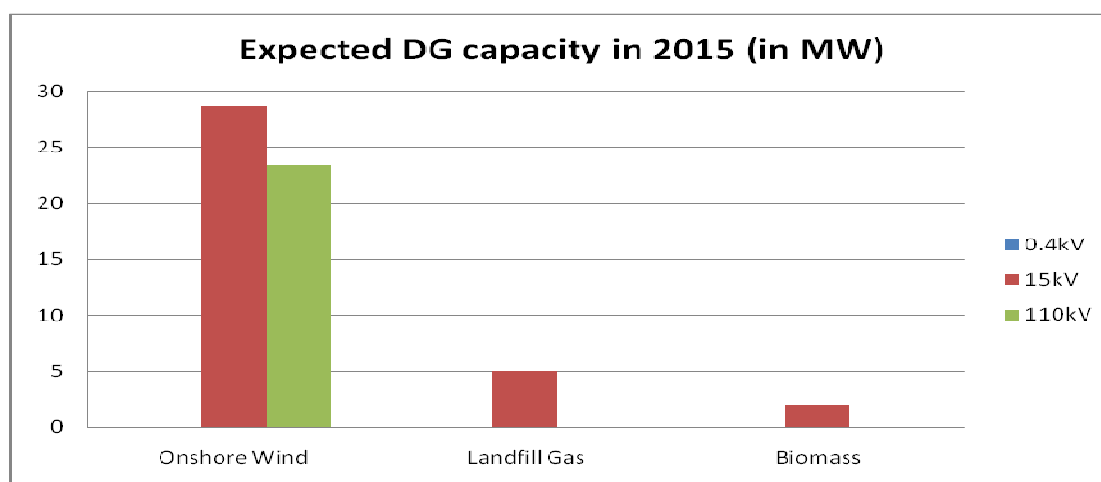


Figure 3.2. Expected DG capacity in 2015.

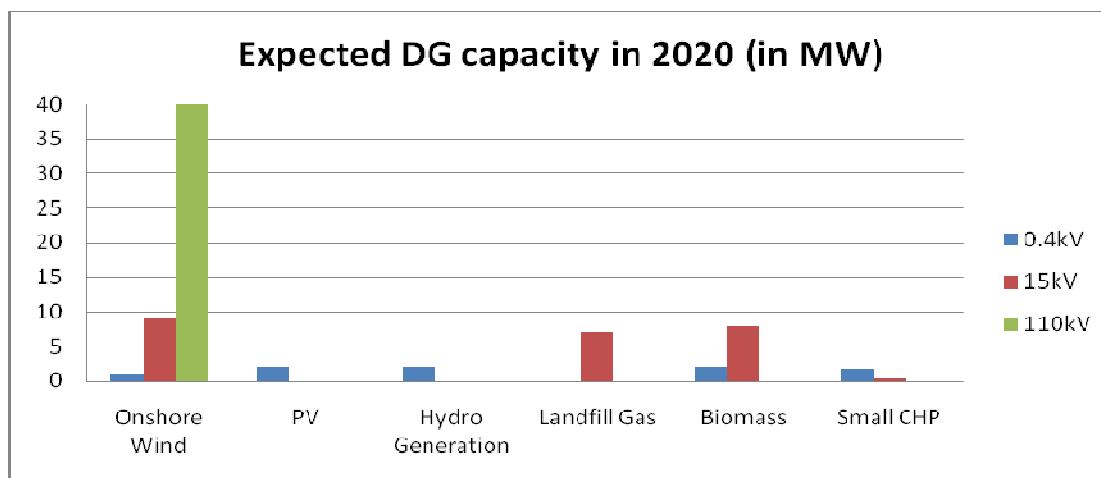


Figure 3.3. Expected DG capacity in 2020.

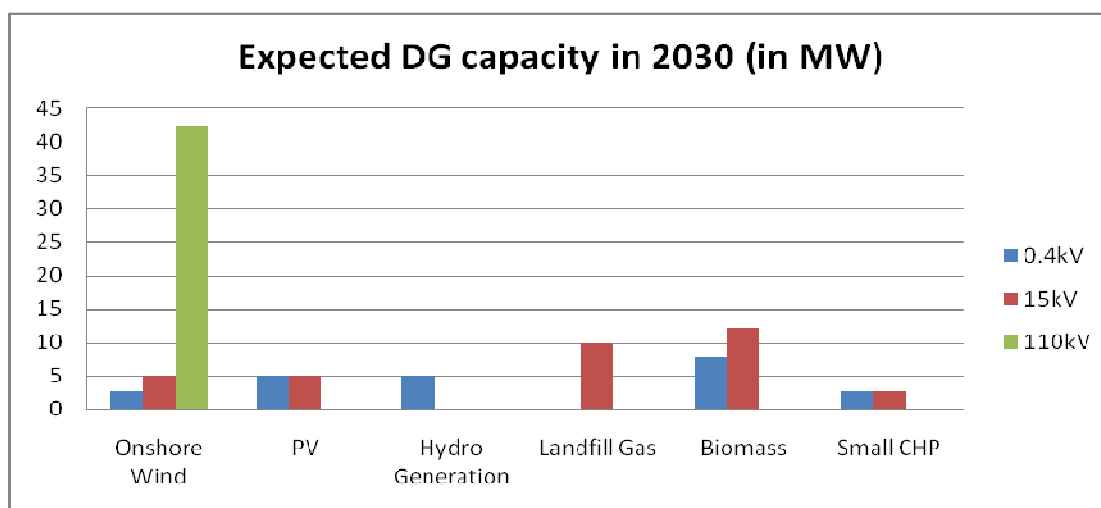


Figure 3.4. Expected DG capacity in 2030.

### 3.1.2 Benefits Related to Reinforcement Cost

The reduction in the reinforcement cost (calculated as described on the main deliverable) by the installation of DG (with regard to the no DG case) in the time window 2010-2015 is depicted on Figure 3.5 (total reduction) and Figure 3.6 (reduction per voltage level).

All the problems arising at the network under every scenario are related to violations of voltage limits. In the no DG case, all of these are voltage drop problems (caused by the demand); after the installation of DG, voltage drop problems are reduced, but some voltage rise problems occur at 15kV (at feeders where large wind turbines are connected). Under passive management, this trend results in higher reinforcement cost in the DG case (Figure 3.5), because the feeders required for resolving the voltage rise problems are more expensive than the reduction in the cost of feeders required for resolving the voltage

drop problems (as shown on Figure 3.7). Under active management, the reinforcement cost in the DG case is much lower (Figure 3.5), since the cost of implementing this strategy is very low compared to the replacement of feeders, deployed under passive management. Active management without tap changers constitutes the least-cost option (Figure 3.5), since it gives much lower reinforcement cost for the 0.4kV (as discussed in the main deliverable, this happens because the voltage problems at this voltage level are very light; in total, only 3.89MVAR are needed for resolving them), even though it gives very slightly higher reinforcement cost for the 15kV (because the voltage problems at this level are severe; in total, 15.56MVAR are needed for resolving them), in comparison with active management with tap changers.

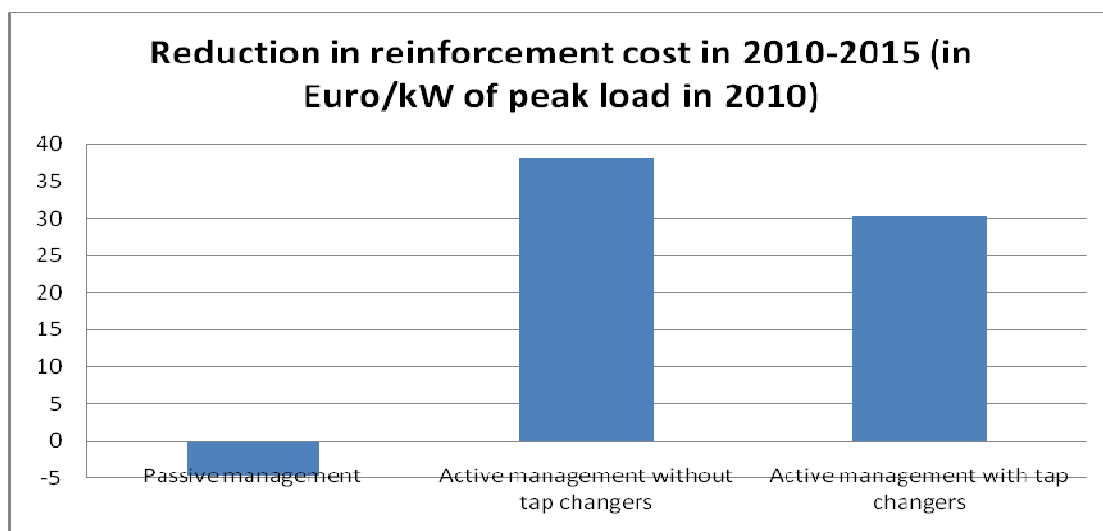


Figure 3.5. Reduction in reinforcement cost in 2010-2015.

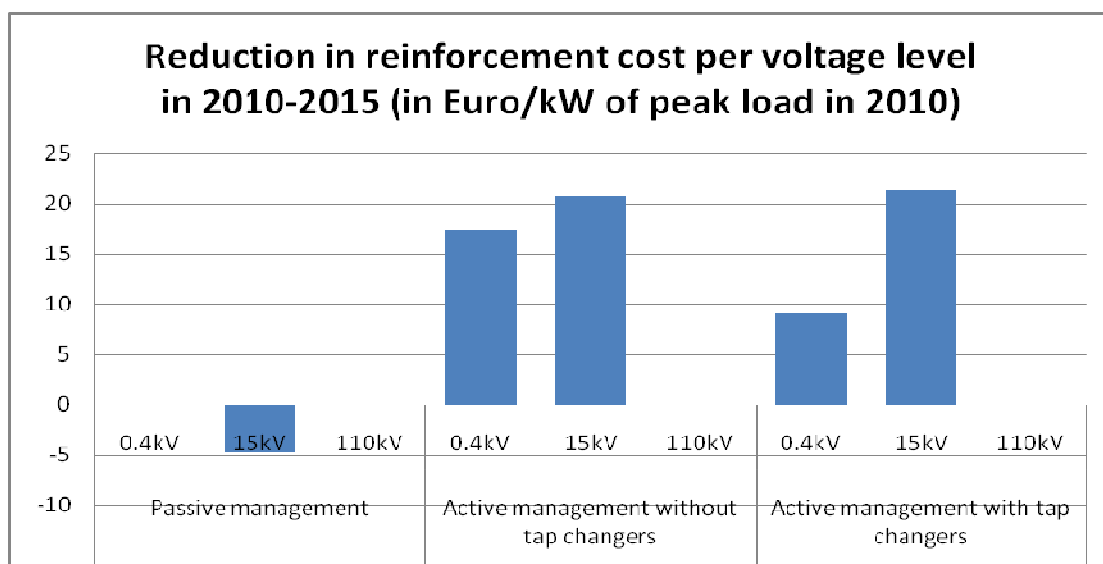


Figure 3.6. Reduction in reinforcement cost per voltage level in 2010-2015.

Due to the fact that voltage rise problems arise after the installation of DG, active management also includes curtailment of distributed generation; since the GDS simulation with the 2010 demand and DG gives us the annual energy curtailment for 2010 (and its cost), we have used an interpolation method in order to project the energy curtailment (and its cost) in each of the years 2011, 2012, 2013, 2014, by taking into account the annual increase rate of the load and the annual increase rate of the price of energy (assumed equal to the annual inflation rate). It is worth stressing that the total curtailed energy (in these 5 years) of each involved generator in both active management strategies is less than 2% of its total energy production. The cost of implementing each of the two active management strategies is presented on Table 3.3; we can see that the cost of tap changers is much higher than any other cost component and this is the reason why active management without tap changers constitutes the least-cost option in the time window 2010-2015.

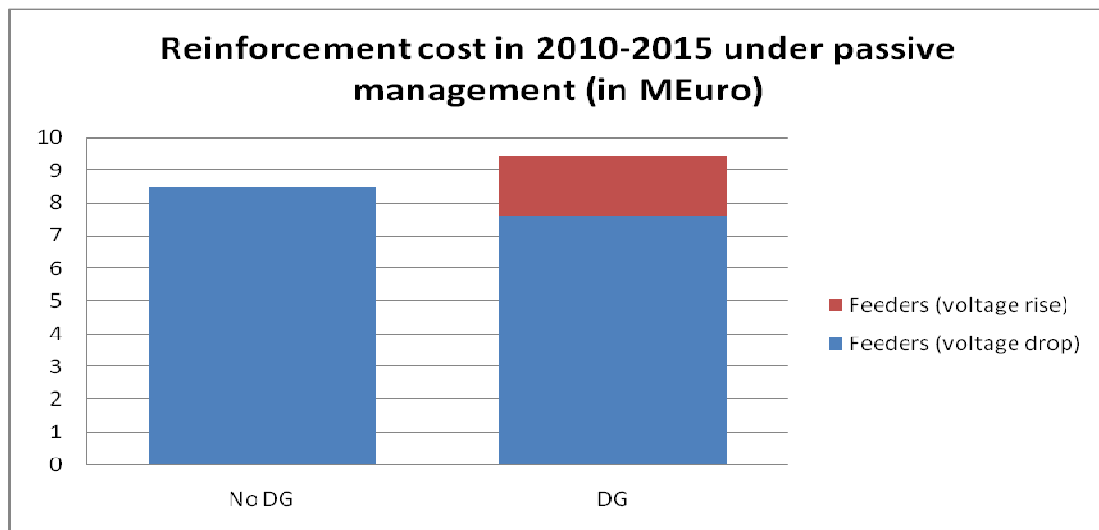


Figure 3.7. Reinforcement cost in 2010-2015 under passive management.

Active management without tap changers	Compensation (capacity cost)	0,301
	Compensation (fixed cost)	0,785
	Curtailment (cost of curtailed energy)	0,052
	Curtailment (fixed cost)	0,007
Active management with tap changers	Compensation (capacity cost)	0,007
	Compensation (fixed cost)	0,004
	Curtailment (cost of curtailed energy)	0,07
	Curtailment (fixed cost)	0,007
	Tap changers (fixed cost)	2,57

Table 3.3. Cost of implementing active management in 2010-2015 (in M€).

The reduction in reinforcement cost in the time window 2015-2020 is presented on Figure 3.8 (total reduction), Figure 3.9 (reduction per voltage level) and Figure 3.9 (reduction per network component-cause of reinforcement). Most of the problems arising

are voltage drop problems at 15kV and there are no voltage rise problems encountered (as in 2010-2015); for the same reasons analyzed above, active management without tap changers gives the lowest reinforcement cost (Figure 3.8). It is very interesting to observe (Figure 3.10) that the cost of reinforcing feeders with thermal problems is higher in the DG case. There are certain feeders in the network which encountered voltage problems in 2010; in the base case (no DG and passive management) these feeders were upgraded (enlarged cross section) while in the DG case they were not, since active management was deployed (active management without tap changers was selected as it was giving the lowest total network cost-see section 3.1.4). Due to the increased demand in 2015, the power flows on these feeders become very high; while in the base case their previous upgrade in 2010 enables them to deal with these flows, in the DG case these flows are higher than their capacity and upgrade is needed in 2015. This is a clear example of **reinforcement deferral** caused by the implementation of active management.

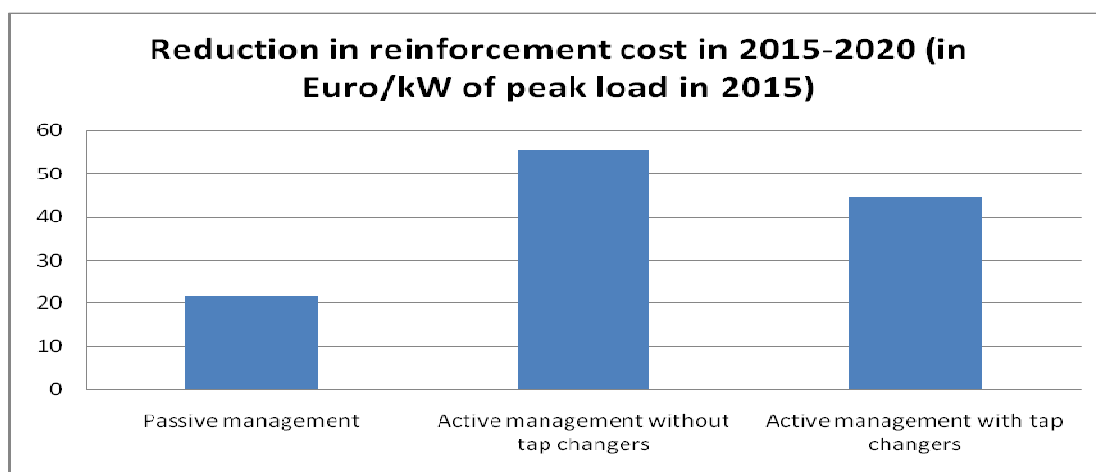


Figure 3.8. Reduction in reinforcement cost in 2015-2020.

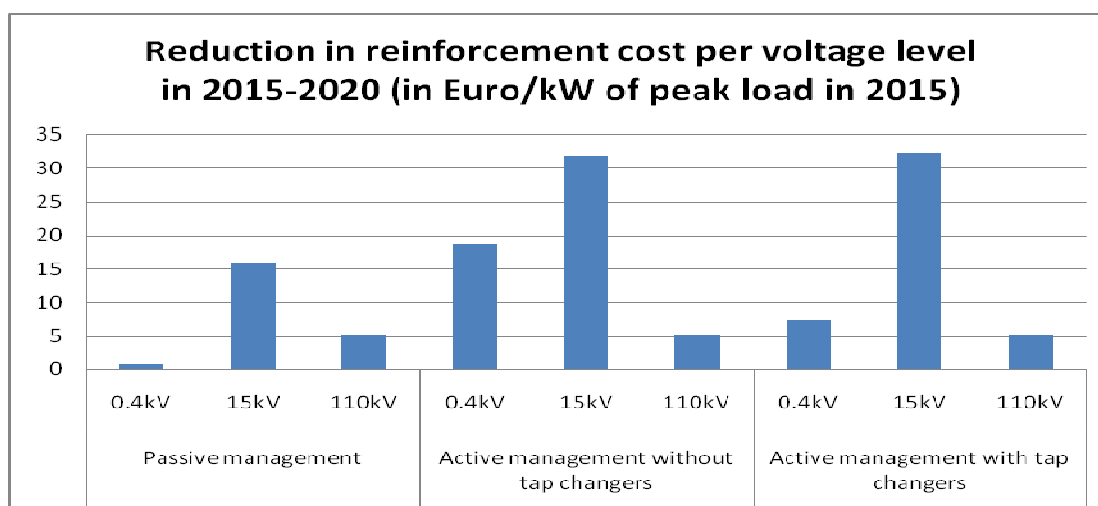


Figure 3.9. Reduction in reinforcement cost per voltage level in 2015-2020.

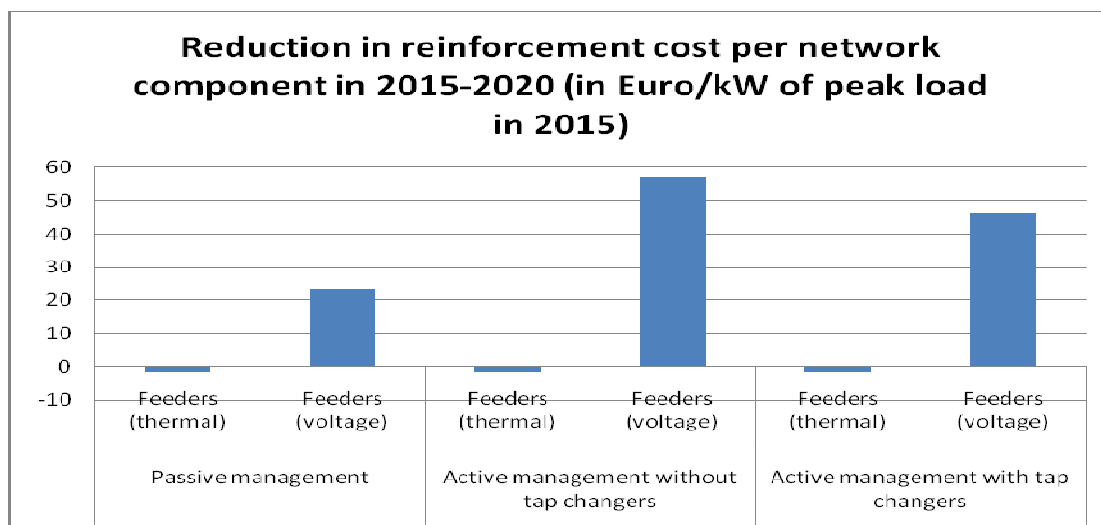


Figure 3.10. Reduction in reinforcement cost per network component in 2015-2020.

Finally, the reduction in reinforcement cost in the time windows 2020-2030 and 2030-2040 is shown on Figure 3.11 and Figure 3.12 (total reduction) and Figure 3.13 and Figure 3.14 (reduction per network component). Similar trends with the previous time windows are observed, with active management without tap changers being the least-cost option (Figure 3.11 and Figure 3.12). While in the no DG case the transformers at 110kV require reinforcement in 2020, in the DG case these transformers require reinforcement in 2030; this is why the reduction in transformers reinforcement cost by the installation of DG is positive in 2020-2030 (Figure 3.13) and negative in 2030-2040 (Figure 3.14). This is a clear example of **reinforcement deferral** caused by the installation of DG.

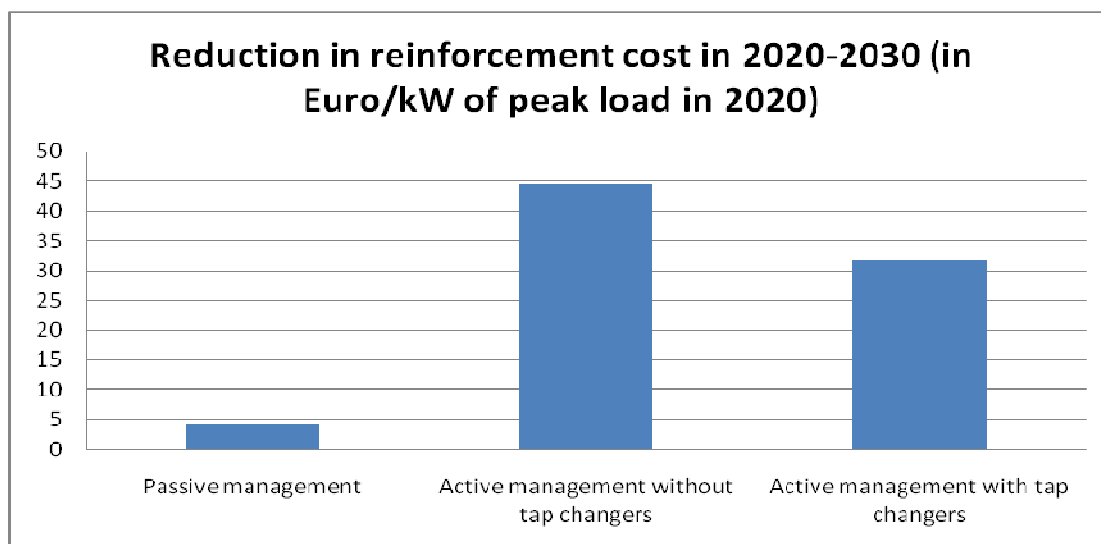


Figure 3.11. Reduction in reinforcement cost in 2020-2030.

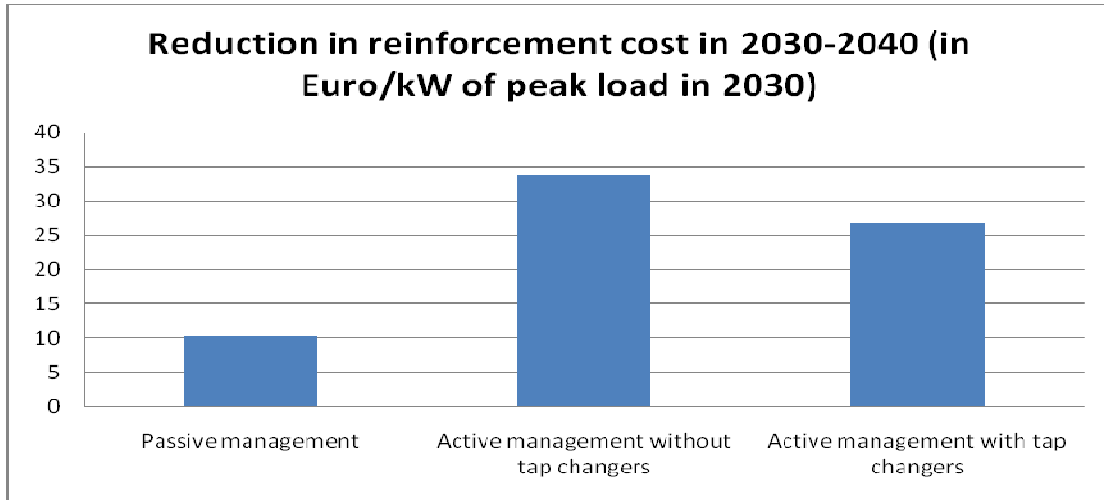


Figure 3.12. Reduction in reinforcement cost in 2030-2040.

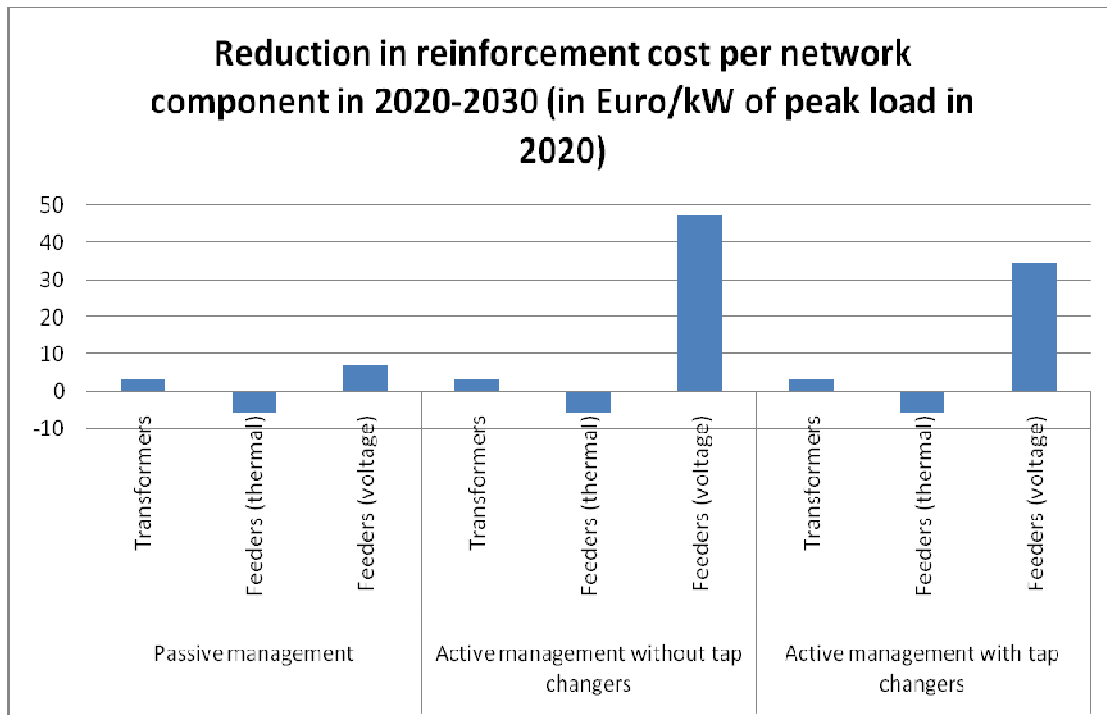


Figure 3.13. Reduction in reinforcement cost per network component in 2020-2030.

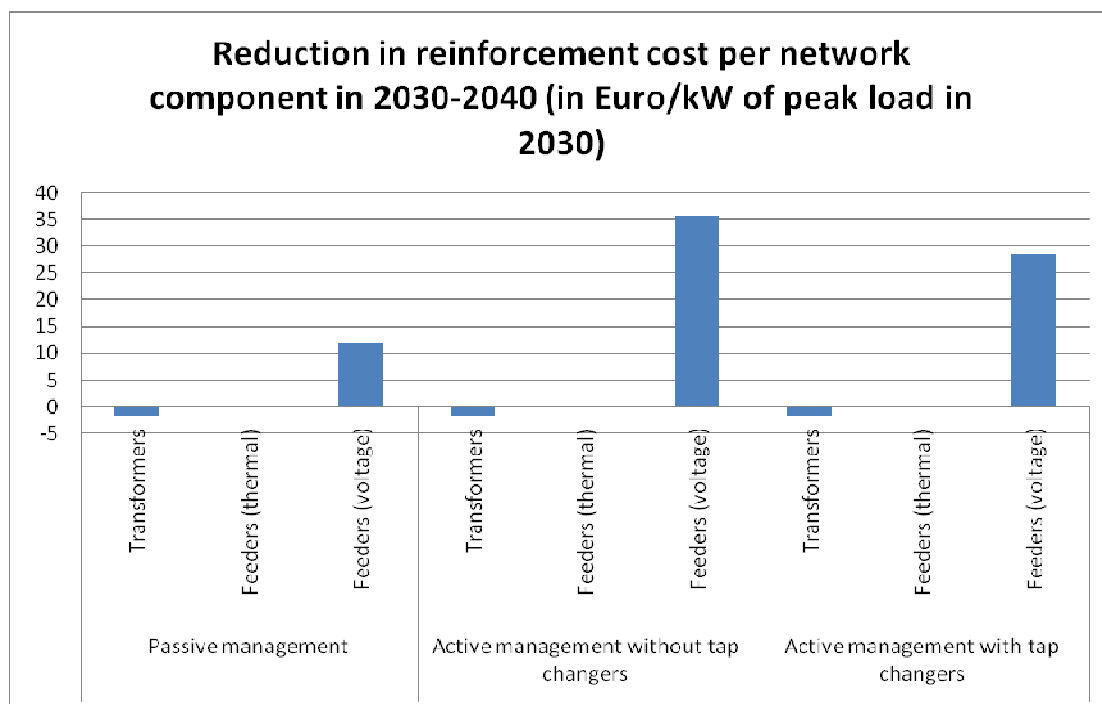


Figure 3.14. Reduction in reinforcement cost per network component in 2030-2040.

### 3.1.3 Benefits Related to Losses

The losses reduction by the installation of DG under each operating strategy in 2010 is depicted on Figure 3.15 (total reduction), Figure 3.16 (reduction per voltage level) and Figure 3.17 (reduction per network component). Losses under passive management are lower (Figure 3.15) because in this case the voltage problems arising (see section 3.1.2) are solved by replacing the suffering feeders with feeders of smaller resistance (while under active management existing feeders are not replaced) and (active) losses of the network depend highly on the resistance of its assets. Furthermore, at 15kV -where severe voltage drop problems at very long, overhead lines arise-, when capacitive compensation alone is used for resolving these problems, its required capacity is high enough to create significant reverse power flows at the feeder it is connected to and consequently increase the losses at this feeder; this is the reason why active management without tap changers is characterized by higher losses than active management with tap changers (and as we can see on Figure 3.15, losses under this strategy are even higher than losses in the no DG case). These two differences in losses between the different strategies are apparent at 0.4kV and 15kV voltage levels (Figure 3.16) since voltage problems and consequently feeders' replacement and connection of capacitive compensation occur at these parts of the network (see section 3.1.2); since such voltage problems do not occur at 110kV, the reduction of the power flow from the GSP to the demand (caused by the installation of DG) results in similar losses reduction in this voltage level under each operating strategy. Moreover, since these differences are related

to feeders’ constraints, they do not affect the transformers’ losses, as shown on Figure 3.17.

Reduction in the cost of losses in the time window 2010-2015 (Figure 3.18) follows the same trends as the losses reduction in 2010.

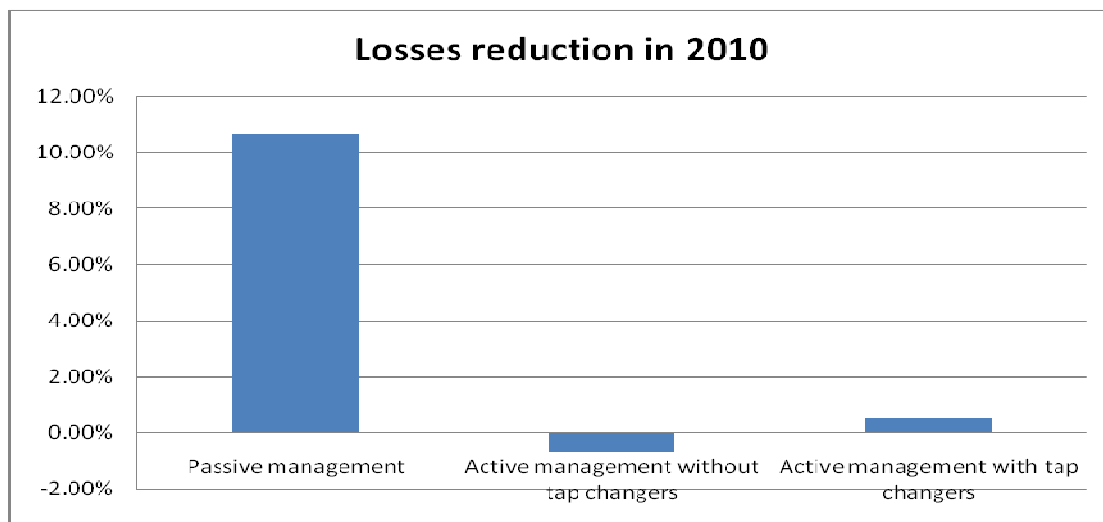


Figure 3.15. Losses reduction in 2010.

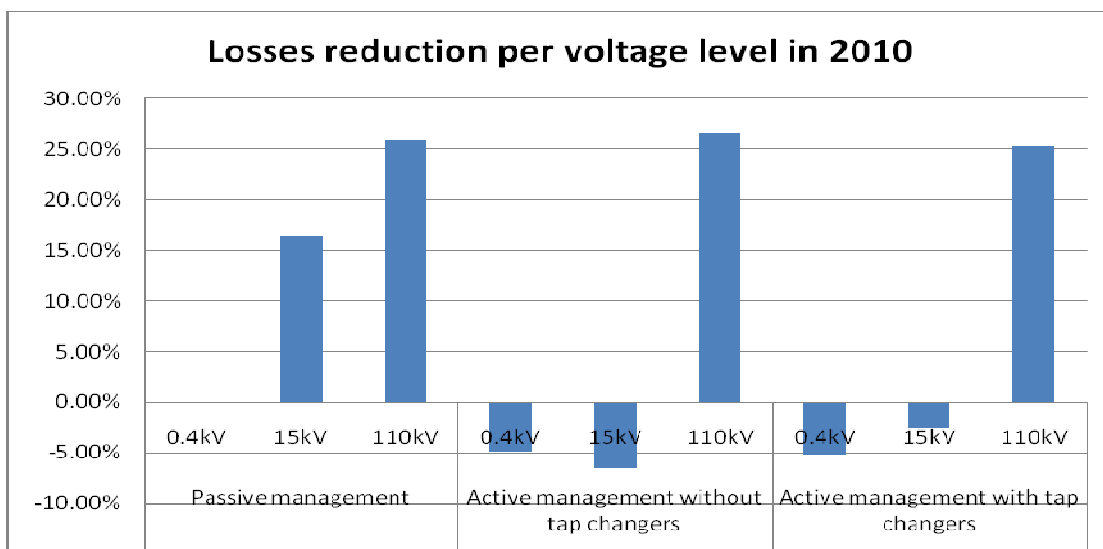


Figure 3.16. Losses reduction per voltage level in 2010.

Similar trends are observed for the losses reduction in 2015, 2020 and 2030 (Figure 3.19, Figure 3.20 and Figure 3.21, respectively); we can see that under every strategy (even passive management), the losses in the DG case are higher than in the base case (no DG), even though DG reduces the power flows from the GSP to the demand. This is because in the base case passive management is deployed in each yearly snapshot, while the evolution of the network with DG is based on the strategy giving the lowest network cost

in each snapshot; since active management without tap changers is the optimal strategy in each snapshot in this network (see the results of section 3.1.4), the network with DG carries a significant amount of capacitive compensation and feeders of large resistance when we move from one examined snapshot to another and thus its losses throughout the years are higher. For example, the losses in the DG case in 2015 under passive management are higher than the losses in the no DG case in the same year (Figure 3.19), because active management without tap changers is deployed in the DG case in the previous snapshot (2010).

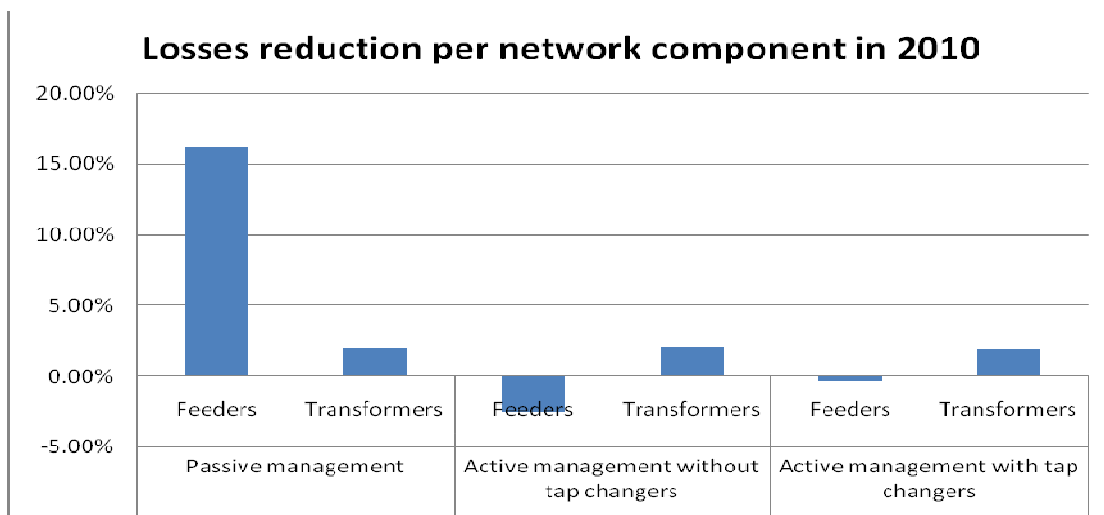


Figure 3.17. Losses reduction per network component in 2010.

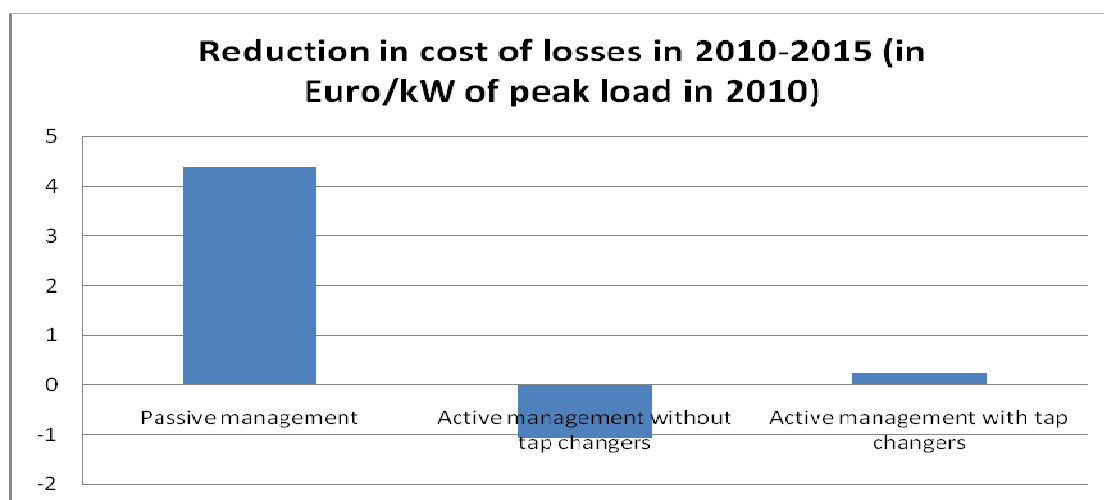


Figure 3.18. Reduction in cost of losses in 2010.

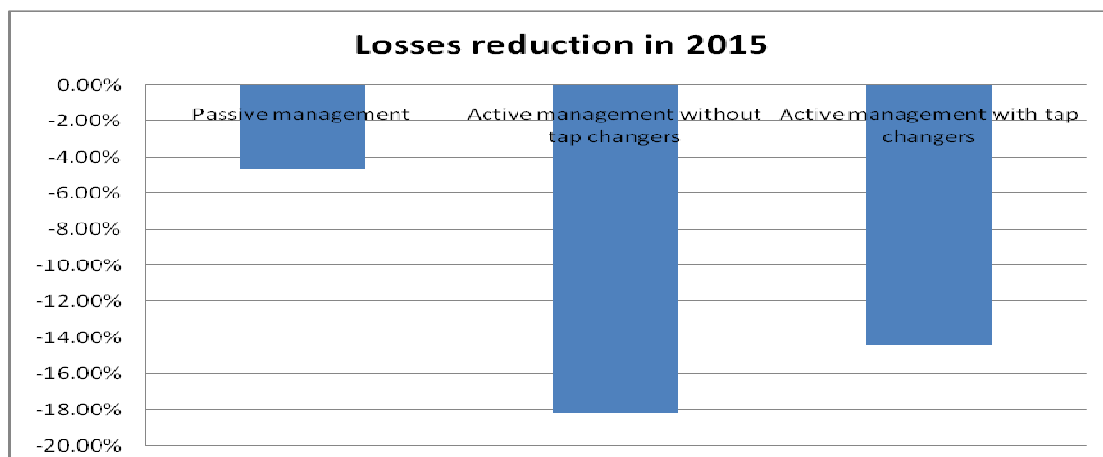


Figure 3.19. Losses reduction in 2015.

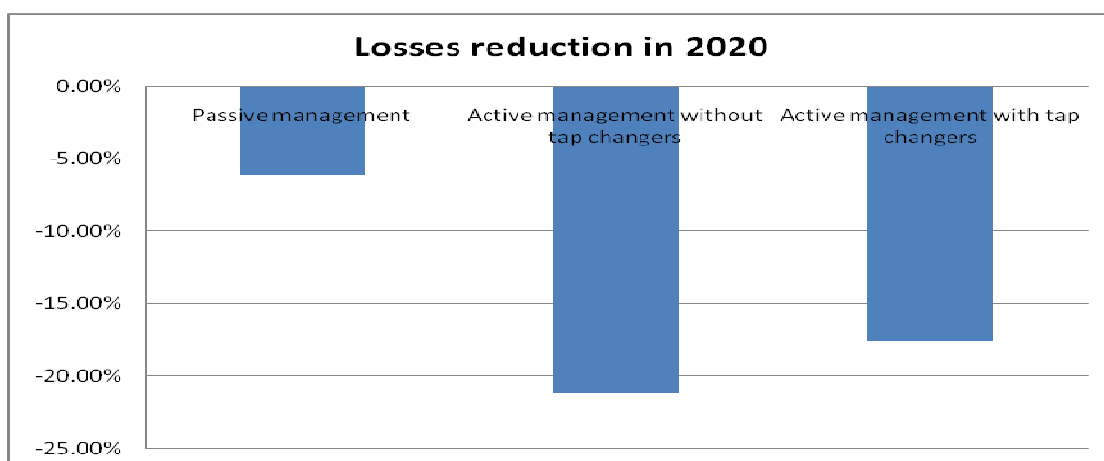


Figure 3.20. Losses reduction in 2020.

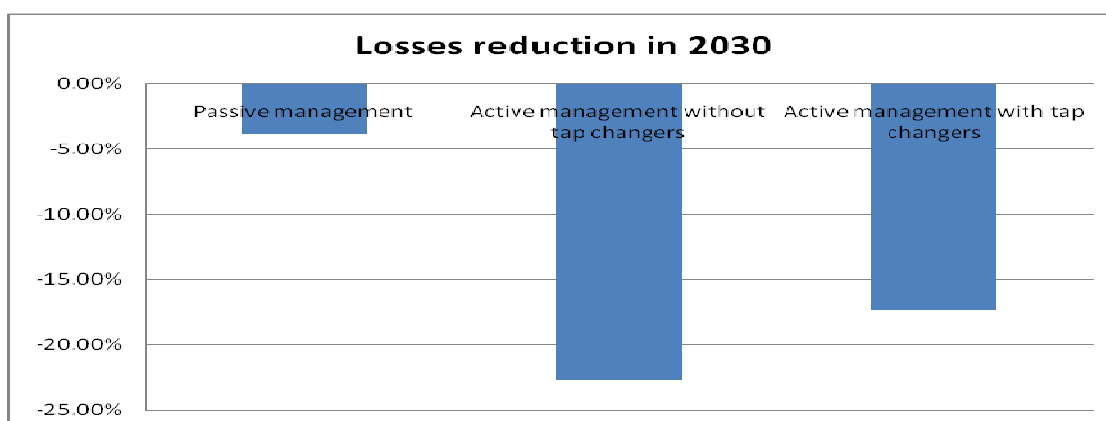


Figure 3.21. Losses reduction in 2030.

### 3.1.4 Benefits Related to Total Network Cost

The reduction in total network cost (sum of the reduction in reinforcement cost and the reduction in the cost of losses) by the installation of DG in each of the examined time windows is presented on Figure 3.22 to Figure 3.25. We can see that the total network cost in the DG case is always lower than the respective one in the no DG case, apart from the time window 2010-2015 under passive management (Figure 3.22) where reinforcement cost is higher in the DG case due to the voltage rise problems arising from the connection of some large wind turbines at 15kV (see section 3.1.2). Moreover, we observe that in the DG case, active management without tap changers is characterized by the lowest network cost in every time window; even though the cost of losses is lower under passive management (see section 3.1.3), the reinforcement cost is much lower in active management without tap changers (see section 3.1.2).

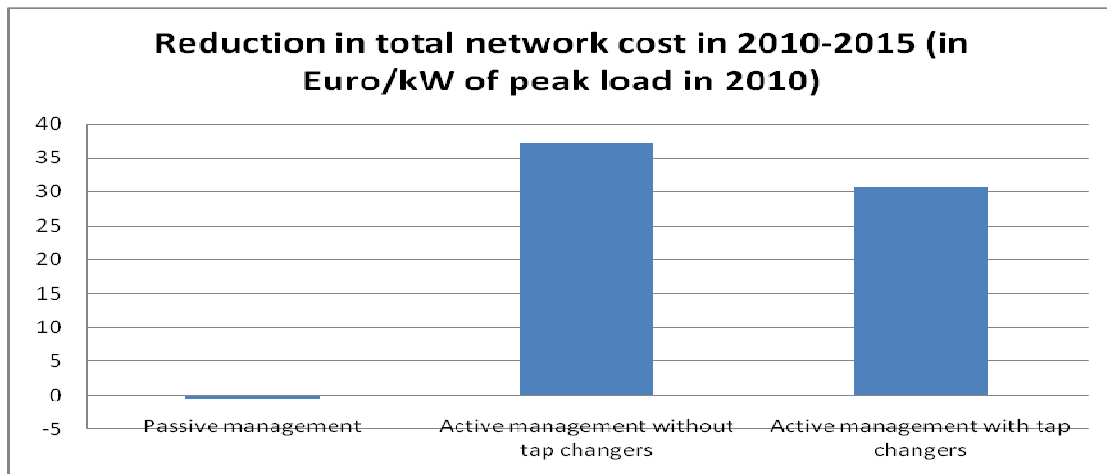


Figure 3.22. Reduction in total network cost in 2010-2015.

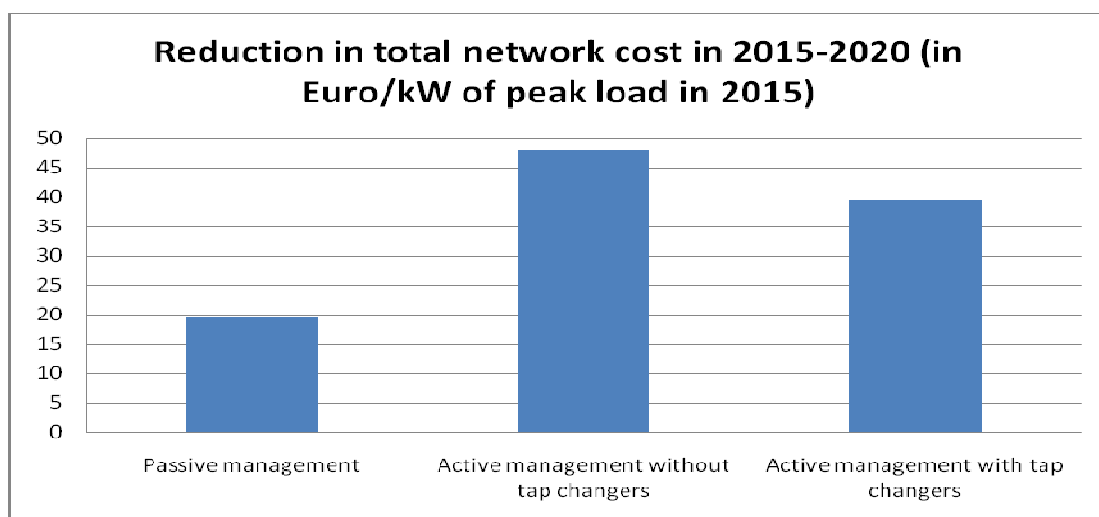


Figure 3.23. Reduction in total network cost in 2015-2020.

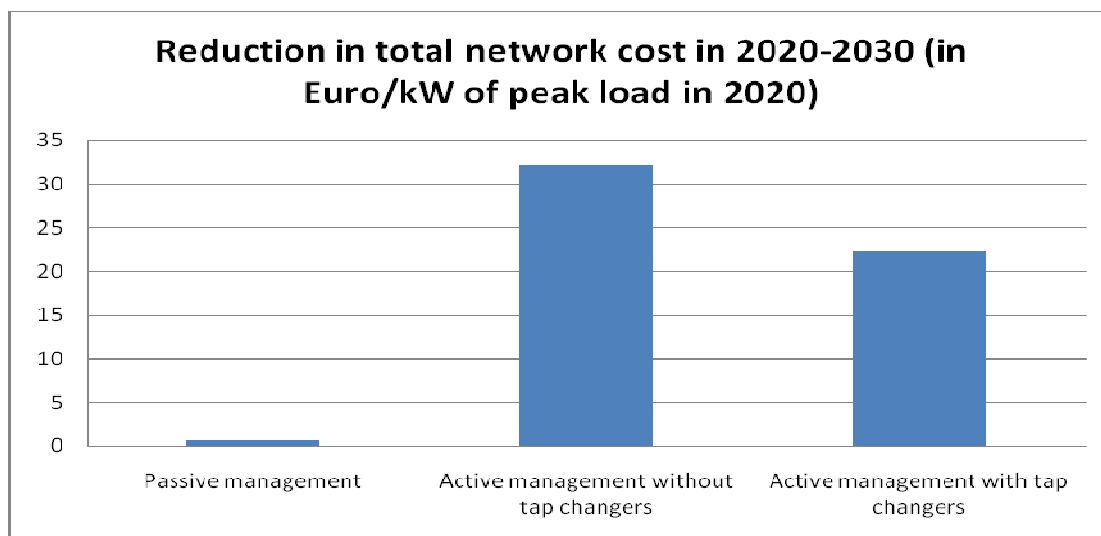


Figure 3.24. Reduction in total network cost in 2020-2030.

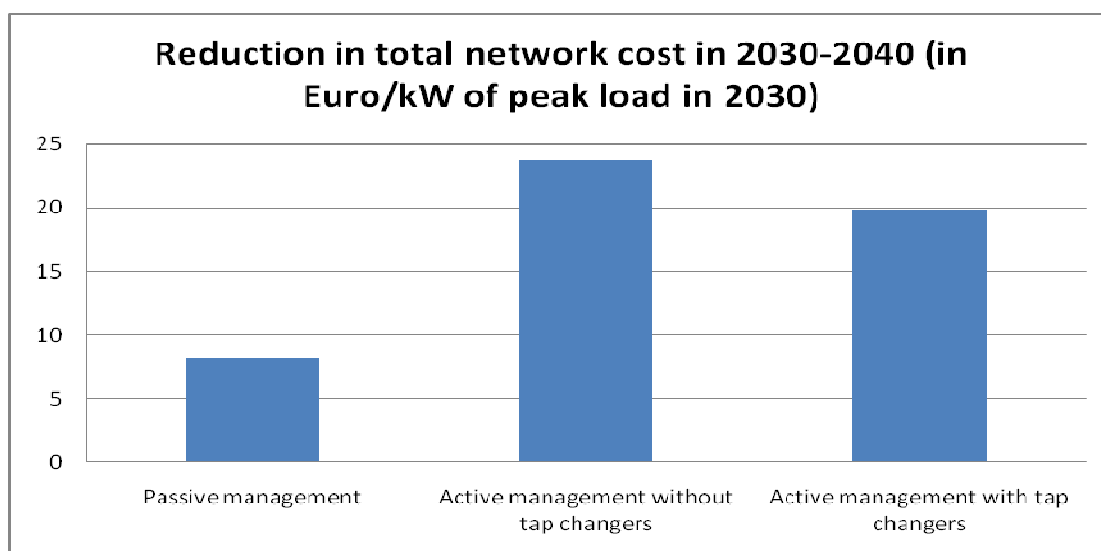


Figure 3.25. Reduction in total network cost in 2030-2040.

### 3.1.5 Benefits Related to Local Power Generation

The annual energy production by each type of DG in each of the examined yearly snapshots is found on Figure 3.26 to Figure 3.29 (for simplicity reasons only for the optimal operating strategy, which is active management without tap changers in any case, according to the results of section 3.1.4). As we saw in section 3.1.2, energy curtailment takes place only in 2010 and it involves some large wind turbines at 15kV; as depicted on Figure 3.26 the annual curtailed wind energy is very low compared to the total annual energy production from wind turbines (more specifically the curtailed energy is equal to 0.71% of the total wind production). The technologies with the largest energy production

throughout the years are onshore wind (due to the significant capacity of wind turbines installed in the network - see section 3.1.1) and biomass (due to the profile of biomass plants in this network - their load factor is equal to one). The percentage of demand covered by DG increases as the years pass by (from 10.22% in 2010 to 17.94% in 2030), as depicted on Figure 3.30, since the DG penetration increases faster than the demand.

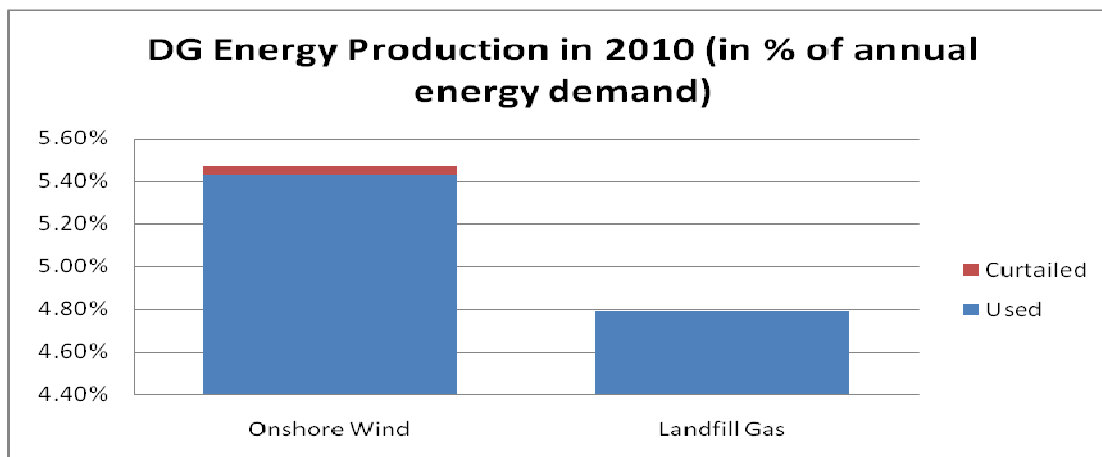


Figure 3.26. DG energy production in 2010.

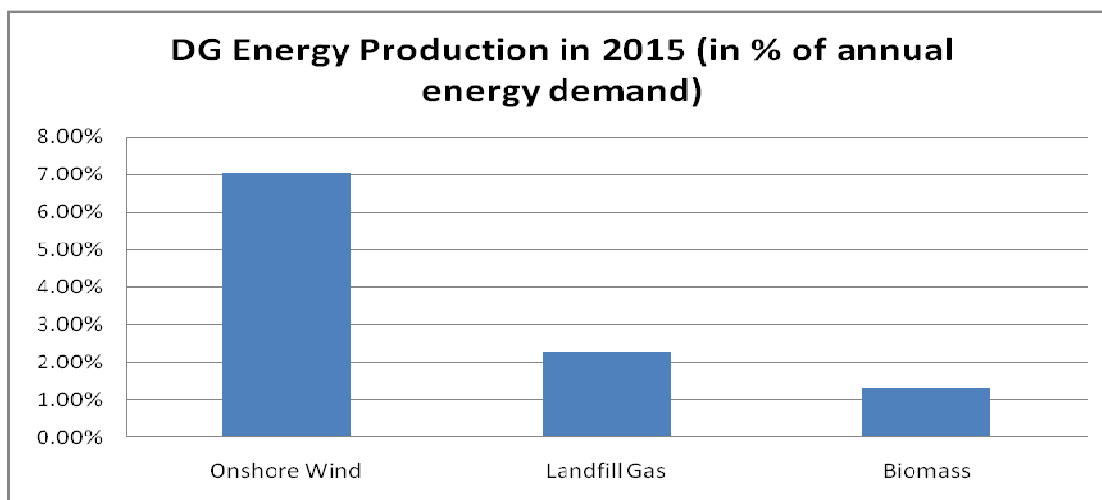


Figure 3.27. DG energy production in 2015.

The hourly profile of the power flowing on the GSP (which expresses the demand curve of the examined distribution network since the GSP constitutes the boundary between the examined distribution network and the upward transmission network) in a winter weekday (period of highest demand in the distribution network) in 2010 is depicted on Figure 3.31 (for simplicity reasons only for the optimal operating strategy, which is active management without tap changers in any case, according to the results of the section 3.1.4). We can observe that the installation of DG: i) decreases the yearly maximum power flow on the GSP (peak of the hourly profile), which is particularly

relevant for transmission investment decisions and ii) moves downwards the whole demand curve of the examined network without changing significantly its shape, which is particularly relevant for central generation scheduling decisions. Same trends are observed in 2015, 2020 and 2030.

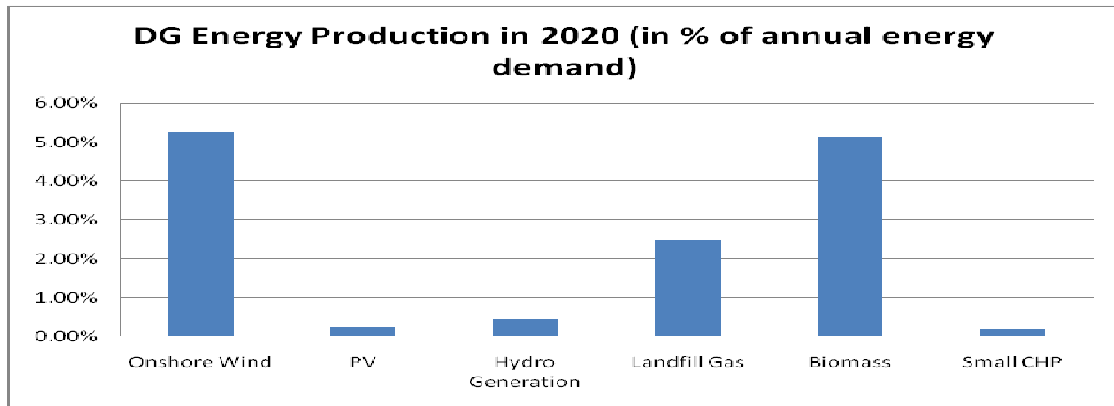


Figure 3.28. DG energy production in 2020.

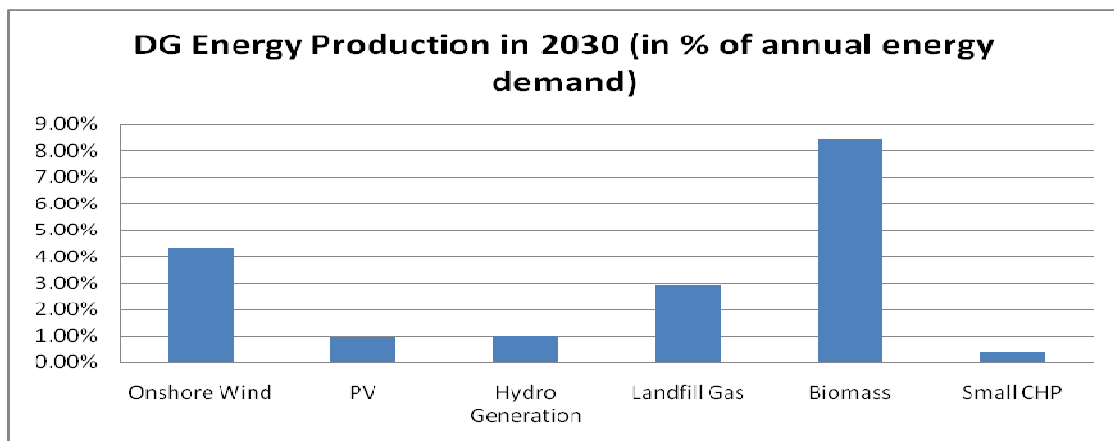


Figure 3.29. DG energy production in 2030.

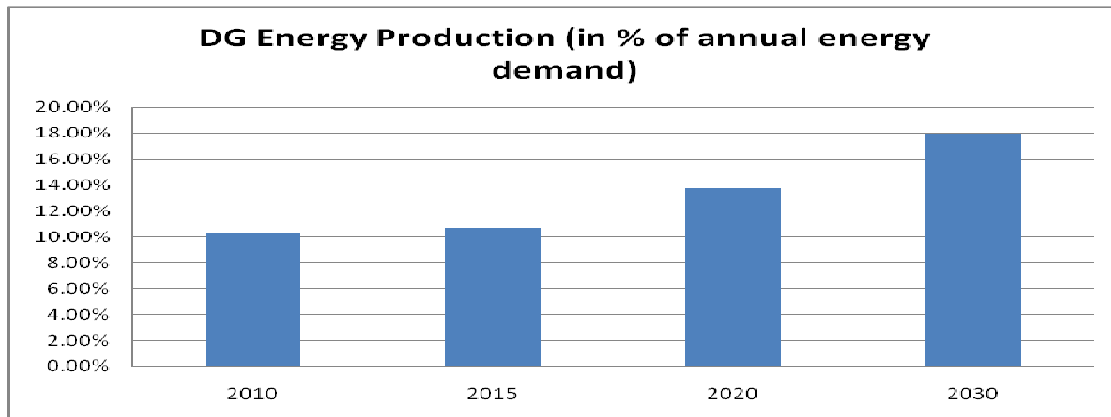


Figure 3.30. DG energy production.

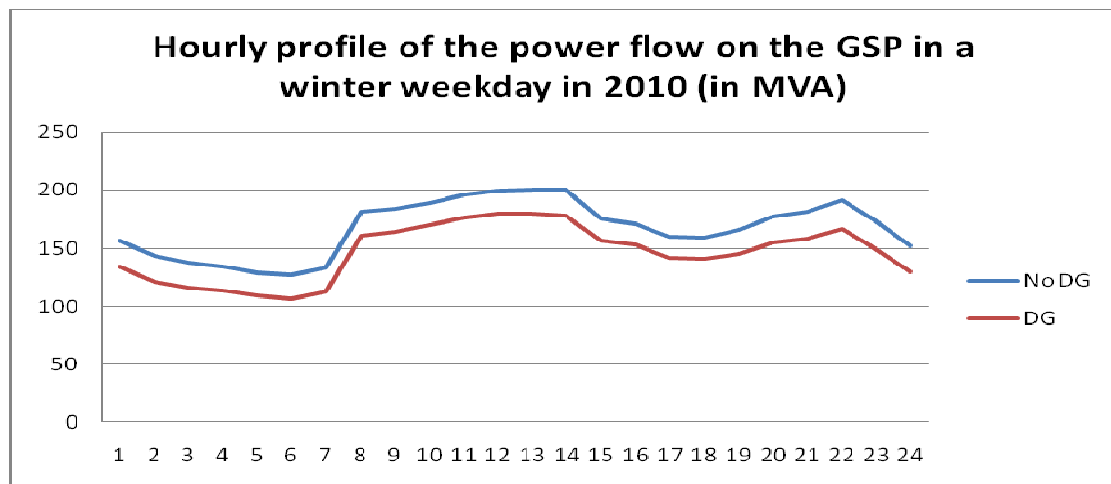


Figure 3.31. Hourly profile of the power flow on the GSP.

### 3.1.6 Environmental Benefits

As explained in detail in the main deliverable, the installation of DG results in  $CO_2$  emissions reduction because i) it reduces losses and ii) it displaces part of the central electricity production (micro CHP generators also displace part of the heat production of conventional boilers); the marginal plant model (presented main deliverable) and a parametric analysis (for different values of the emission factor of the marginal plant) is used for the calculation of this reduction.

The  $CO_2$  emissions reduction (with respect to the no DG case) caused by renewable energy production (onshore wind turbines, PV panels and hydro generators) and combined heat and power energy production (biomass and landfill plants, small CHPs), by the reduction of losses and the total one are presented on Figure 3.32 to Figure 3.35 for each examined yearly snapshot (for simplicity reasons only for the optimal operating strategy, which is active management without tap changers in any case, according to the results of section 3.1.4). As described by the relevant equations in the main deliverable, we observe that the emissions reduction caused by local power generation (both

renewable generation and cogeneration) increases linearly with the emission factor of the marginal plant. Since losses in the DG case are higher than losses in the no DG case in each of the examined yearly snapshots (see section 3.1.3), the emissions reduction related to losses is negative in each of the following Figures and decreases linearly as the emission factor of the marginal plant increases. The positive impact of local power generation on emissions is much more significant than the negative impact of losses, and consequently the total emissions reduction is positive in each of the examined yearly snapshots.

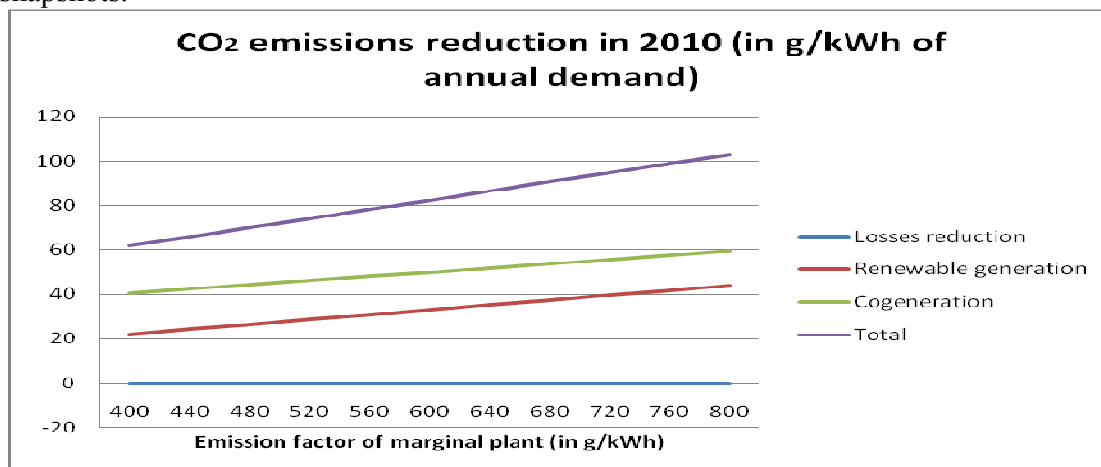


Figure 3.32. CO<sub>2</sub> emissions reduction in 2010.

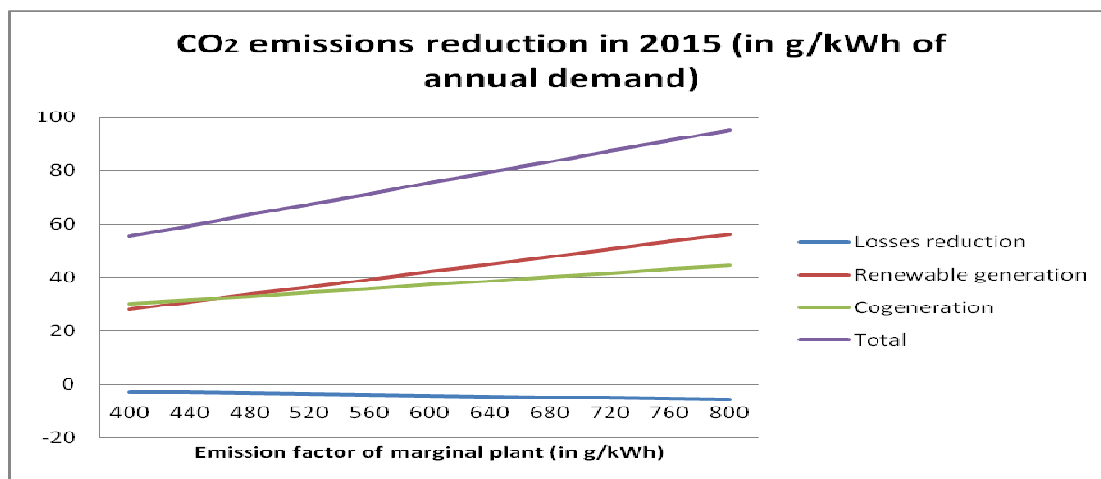


Figure 3.33. CO<sub>2</sub> emissions reduction in 2015.

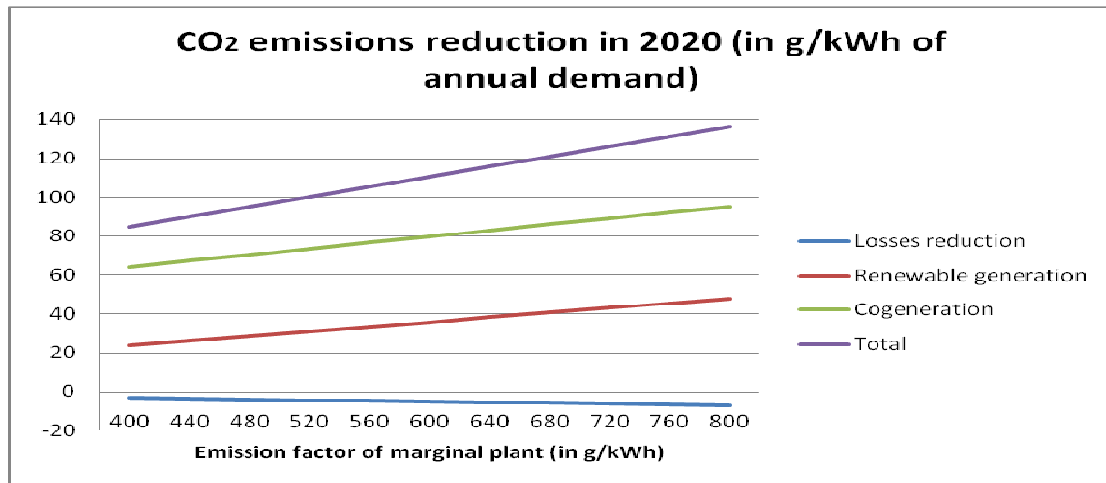


Figure 3.34. CO<sub>2</sub> emissions reduction in 2020.

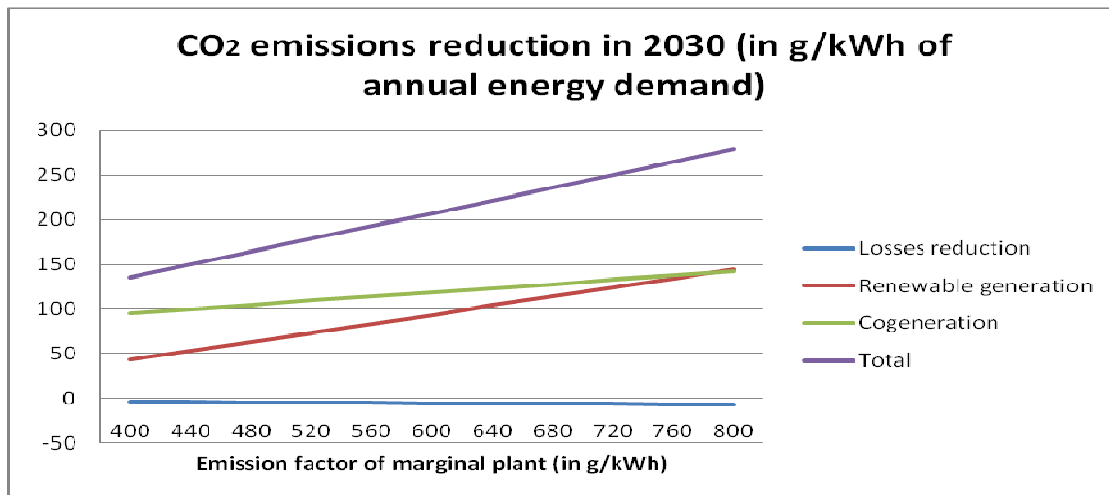


Figure 3.35. CO<sub>2</sub> emissions reduction in 2030.

### 3.1.7 Conclusion

The main component of DG penetration in the Polish distribution network in the following 20 years is **onshore wind turbines** at the medium and high voltage levels, followed by **landfill gas and biomass plants** (with flat profiles) at the medium voltage level; a small penetration of micro DG is expected to take place after 2020 (Figure 3.1 to Figure 3.4). The percentage of the annual energy demand covered by DG increases throughout the years, since DG penetration increases faster than the demand (Figure 3.30). Our dynamic analysis on the Polish distribution network shows that the large majority of the required **reinforcement** in each of the examined time windows is related to **violations of voltage limits** caused by demand (voltage drop), with the most severe problems arising at the **medium voltage level**, since it is characterized by many long, overhead lines. Reinforcement driven by the installation of DG is only encountered in

2010, when some large wind turbines are connected to weak 15kV feeders; even though the installation of DG in this year mitigates the voltage drop problems, these voltage rise problems are so severe that it increases the total reinforcement cost in the time window 2010-2015 under passive management (Figure 3.5 and Figure 3.7). In the rest of the examined time windows the problems arising are caused by demand, and consequently DG reduces reinforcement cost, by mitigating these problems (Figure 3.8, Figure 3.11 and Figure 3.12). The dynamic nature of our analysis enables us to witness not only **reinforcement cost reduction**, but also **reinforcement deferral by the installation of DG**: in the base case (no DG), the 110kV transformers need reinforcement in 2020 while in the test case (with DG), they reinforcement in 2030 (Figure 3.13 and Figure 3.14).

The deployment of **active management reduces further the reinforcement cost** in each time window, since the cost of implementing the active controls is much lower than the cost of replacing the feeders suffering from voltage problems (Figure 3.5, Figure 3.8, Figure 3.11 and Figure 3.12). The active management strategy giving the lowest reinforcement cost in each of the examined time windows is **AM without tap changers**, because the voltage problems arising are not severe enough to economically justify the installation of tap changers. Active management in the time window 2010-2015 includes **curtailment** of the production of the generators causing voltage rise problems; however, the total curtailed energy of each involved generator is less than 2% of its total energy production during these 5 years. The dynamic nature of our analysis enables us to witness not only reinforcement cost reduction, but also **reinforcement deferral by the deployment of active management**: in the base case (no DG) the replacement of certain heavy-loaded feeders is needed in 2010 because they face voltage problems; in the test case (with DG) this replacement in 2010 is avoided (since active controls are used in order to resolve these problems) and it is deferred in 2015 when the same feeders face thermal problems (Figure 3.10).

**Losses** (and their cost) are **lower under passive management** than under active management and **higher under active management without tap changers** than under active management with tap changers for the reasons explained in section 3.1.2 (Figure 3.15 and Figure 3.18 to Figure 3.21). Since active management without tap changers is deployed in each of the examined yearly snapshots (because it gives the lowest total network cost in each of the examined time windows) in the test case, the network in this case carries such a significant amount of capacitive compensation and feeders of large resistance when we move from one examined snapshot to another and thus its **losses throughout the years are higher than in the base case**, despite the fact that DG reduces the power flows on the distribution network.

Even though the cost of losses is generally higher in the DG case than in the base case, the reinforcement cost is much lower in the former and thus **DG brings a benefit** with regard to the **total network cost** (Figure 3.22 to Figure 3.25). The only exemption can be found in the time window 2010-2015 under passive management, where DG increases the reinforcement cost due to the voltage rise problems it causes. **Active management reduces further the total network cost**, because its positive impact on the reinforcement cost is much more significant than its negative impact on the (cost of) losses; more specifically, **active management without tap changers** is the optimal strategy in each of the examined time windows.

A similar trend is observed in the results concerning the  $CO_2$  emissions: even though the emissions related to losses are higher in the DG case (because losses are higher), the emissions reduction by the displacement of central electricity production with renewable and CHP energy production (and heat production of conventional boilers with CHP energy production) is so high that the **total emissions in the DG case are much lower** (Figure 3.32 to Figure 3.35).

### 3.2 MicroGrid Scenarios

#### 3.2.1 General Information

The same Polish distribution network we have worked with in section 3.1, is used here as well. Two scenarios for the load at LV (low load: +10% and high load: +50% with respect to the current load at LV) and three scenarios for micro DG penetration (Figure 3.36) were investigated.

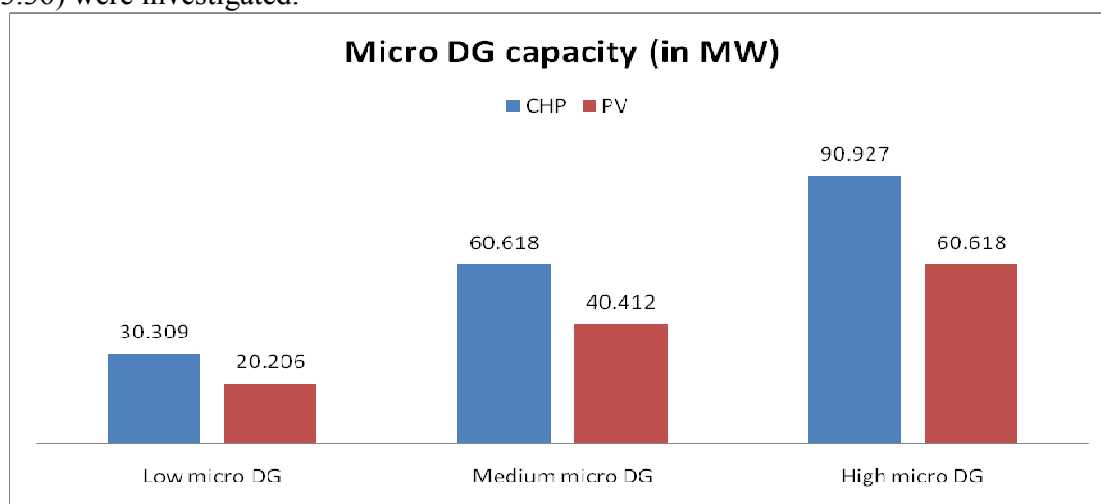


Figure 3.36. Micro DG capacity.

#### 3.2.2 Benefits Related to Reinforcement Cost

The reduction in the annualized reinforcement cost by the installation of micro DG (with regard to the base case) for the low load scenario is depicted on Figure 3.37 (total reduction) and Figure 3.38 (reduction per voltage level).

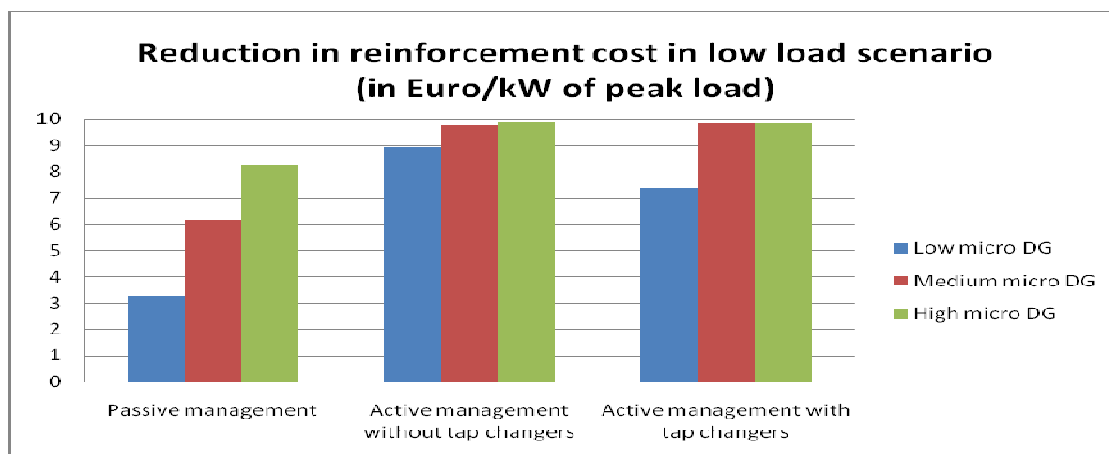


Figure 3.37. Reduction in reinforcement cost in low load scenario.

	0.4kV	15kV	110kV
No micro DG	389	24	0
Low micro DG	389	10	0
Medium micro DG	0	10	0
High micro DG	0	6	0

Table 3.4. Number of feeders suffering from voltage problems in low load scenario.

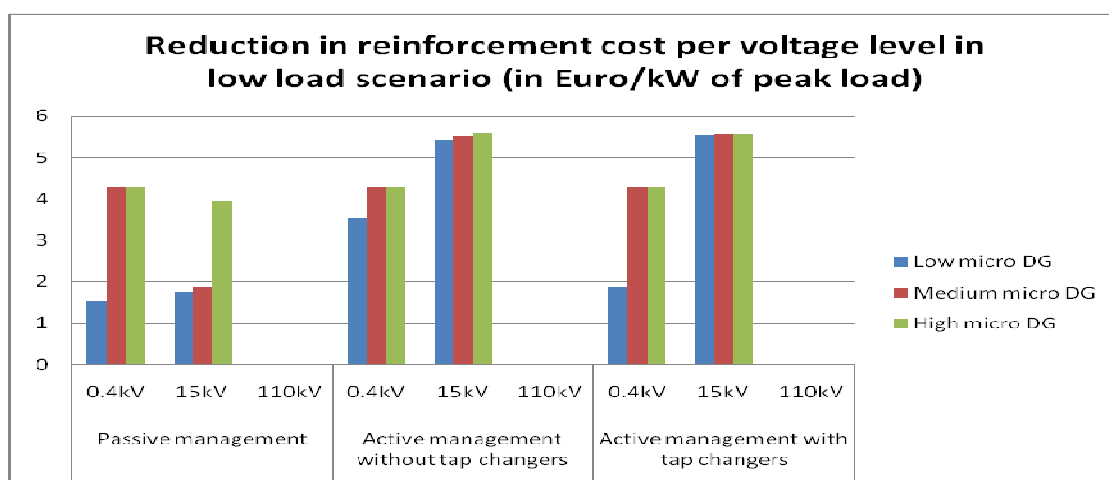


Figure 3.38. Reduction in reinforcement cost per voltage level in low load scenario.

We can see that the reinforcement cost is reduced when micro DG capacity is increased because reinforcement is driven by the demand. The whole reinforcement is related to violations of voltage limits (there are no thermal or fault level problems arising) at 0.4kV and 15kV and Table 3.4 shows the number of feeders suffering from voltage problems in each scenario. In every micro DG scenario, the reduction in reinforcement cost under active management is much higher than the respective one under passive management due to the very low cost of implementing active management in comparison with the cost of replacing the feeders suffering from these voltage problems. This difference becomes

lower when we move from low to high micro DG penetration since these voltage problems become less severe. In the low micro DG scenario, active management without tap changers is the least-cost option since it gives much lower reinforcement cost for the 0.4kV as shown on Figure 3.38 (this happens because the voltage problems at this voltage level are very light; in total, only 0.4MVAR are needed for resolving them). In the medium and high micro DG cases, no problems are encountered in 0.4kV (Table 3.4) and consequently the deployment of different strategies does not alter the reinforcement cost for this voltage level (Figure 3.38) but only the respective cost at 15kV. Since these voltage problems are caused by load (voltage drop problems), their severity decreases when we move from medium to high micro DG penetration; in accordance with our comments in the main deliverable, the cost of deploying active management without tap changers decreases when the severity of the voltage problem decreases (8.05MVAR of reactive compensation are needed in the medium micro DG scenario while only 3.1MVAR are needed in the high micro DG scenario), while the cost of active management with tap changers remains constant (in both scenarios there is no reactive compensation needed and the only parameter changing is the position of the tap changer). As a result of this trend, active management with tap changers gives the lowest reinforcement cost in the medium micro DG scenario and active management without tap changers gives the lowest reinforcement cost in the high micro DG scenario.

The respective results for the high load case are presented on Figure 3.39 and Figure 3.40 and Table 3.5. As in the previous case, reinforcement is driven by demand and is related to voltage drop problems. Similar trends are observed: active management without tap changers gives the lowest reinforcement cost in low and medium micro DG penetration (because the voltage problems at 0.4kV are very light) while active management with tap changers gives the lowest reinforcement cost in high micro DG penetration (the voltage problems at 15kV are severe enough to make the installation of tap changers economically attractive). Since voltage drop problems are more severe now (due to the greater demand), the differences between passive and active management are more obvious than in the low load case.

	0.4kV	15kV	110kV
No micro DG	638	28	0
Low micro DG	389	24	0
Medium micro DG	389	10	0
High micro DG	0	10	0

Table 3.5. Number of feeders suffering from voltage problems in high load scenario.

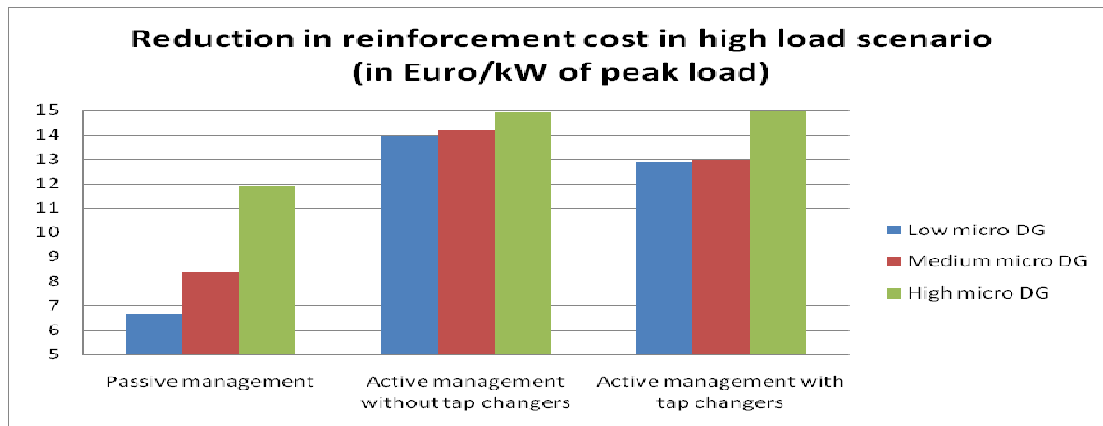


Figure 3.39. Reduction in reinforcement cost in high load scenario.

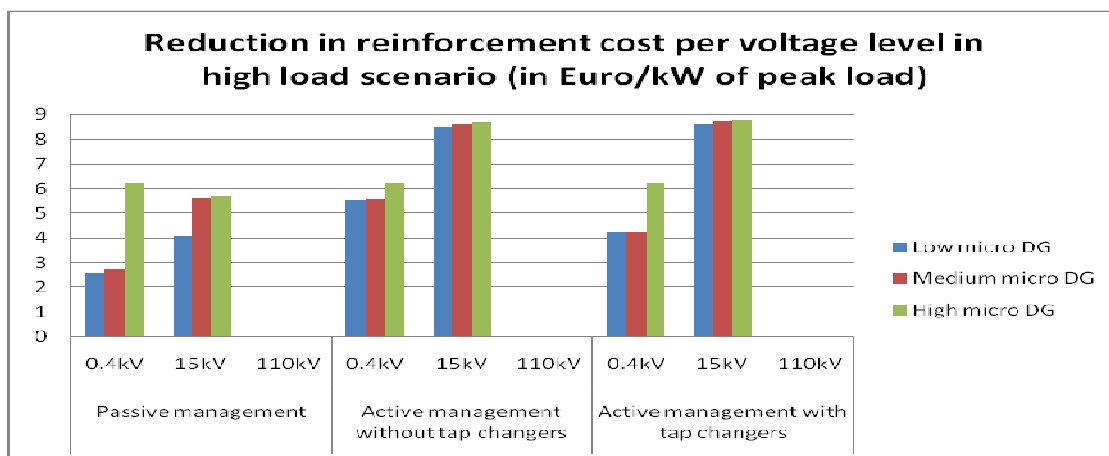


Figure 3.40. Reduction in reinforcement cost per voltage level in high load scenario.

### 3.2.3 Benefits Related to Losses

The losses reduction by the installation of micro DG for the low load scenario under each micro DG scenario and each operating strategy is presented at Figure 3.41. When we increase micro DG penetration, the power flow from the GSP to the demand decreases (as more of the power required by the load is supplied by micro DG) and thus losses are reduced. Losses under passive management are lower in every micro DG scenario, because in this case the voltage problems arising (see section 3.2.2) are solved by replacing the suffering feeders with feeders of smaller resistance (while under active management existing feeders are not replaced) and (active) losses of the network depend highly on the resistance of its assets. Furthermore, losses under active management without tap changers are higher than under active management with tap changers: when only capacitive compensation is used for resolving severe voltage drop problems, its required capacity is high enough to create significant reverse power flows at the feeder it is connected to. This is particularly the case at 15kV, where severe voltage problems at

very long, overhead lines arise; we can see (Figure 3.42) that in the low micro DG case, the losses at this level are higher than the respective losses at the no DG scenario (negative losses reduction). These two differences in losses between the different strategies become less apparent as micro DG penetration is increased, since less voltage problems occur (see Table 3.4 of section 3.2.2) and thus fewer feeders are replaced under passive management and less capacitive compensation is connected at the suffering feeders under active management without tap changers; moreover, since these differences are related to feeders' constraints, they do not affect the transformers' losses significantly, as shown on Figure 3.43.

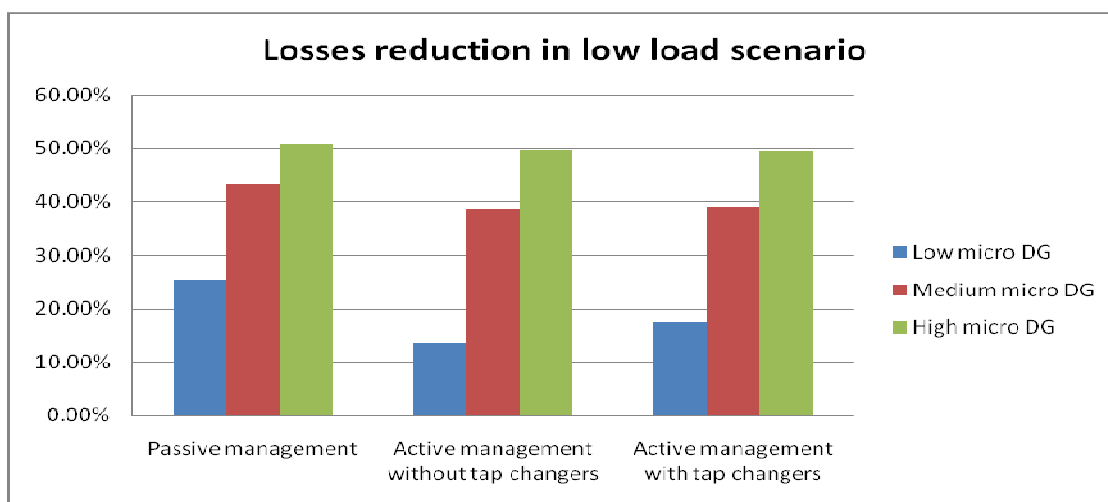


Figure 3.41. Losses reduction in low load scenario.

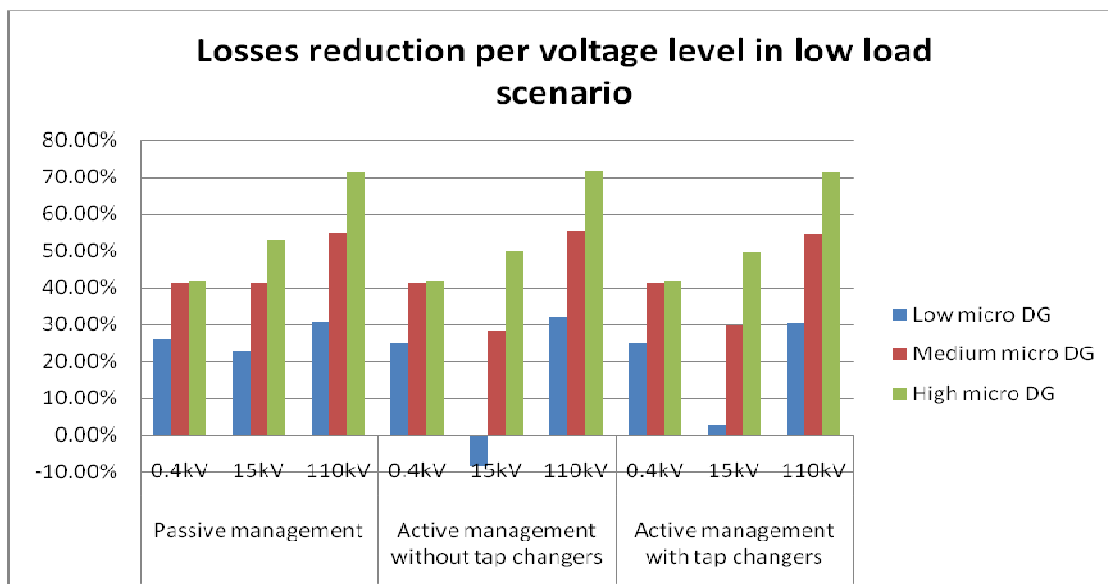


Figure 3.42. Losses reduction per voltage level in low load scenario.

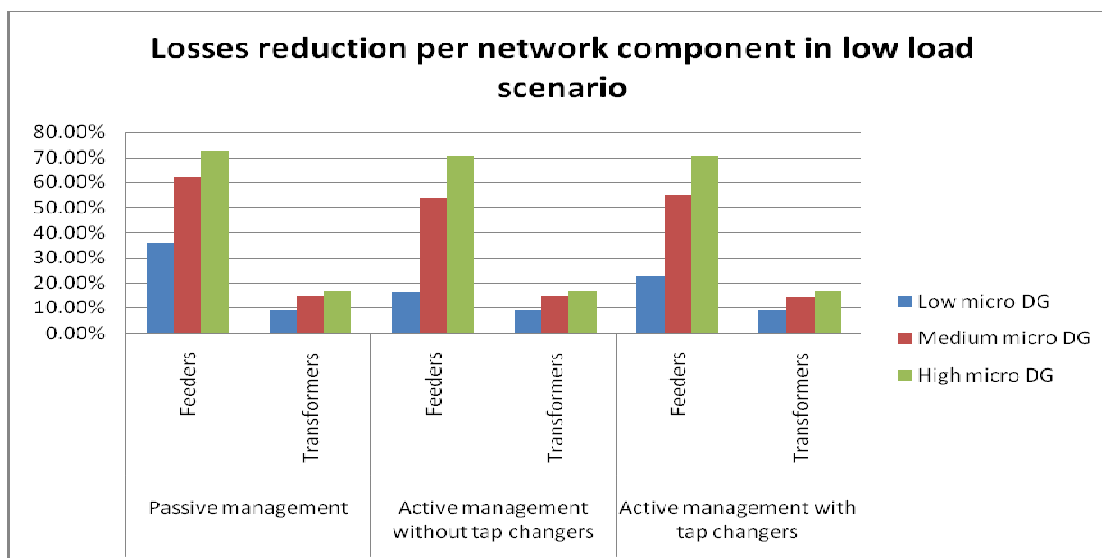


Figure 3.43. Losses reduction per network component in low load scenario.

Reduction in the (annual) cost of losses (Figure 3.44) follows the same trends as the losses reduction since amount and cost of losses are proportional.

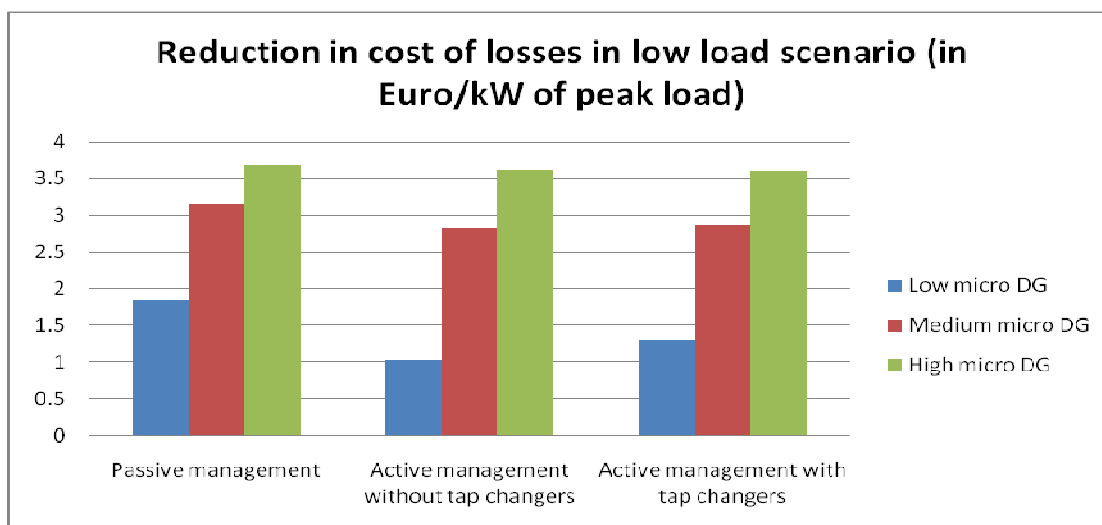


Figure 3.44. Reduction in cost of losses in low load scenario.

The respective results for the high load case are shown on Figure 3.45 to Figure 3.48. Similar trends to the low load case are observed. Since voltage drop problems are more severe now (due to the greater demand), the differences in losses between the different operating strategies are more obvious; it is very interesting to note that in the low micro DG case, the losses under active management without tap changers is increased with respect to the no DG case, due to the very big capacitive compensation capacity connected at long, overhead lines at 15kV.

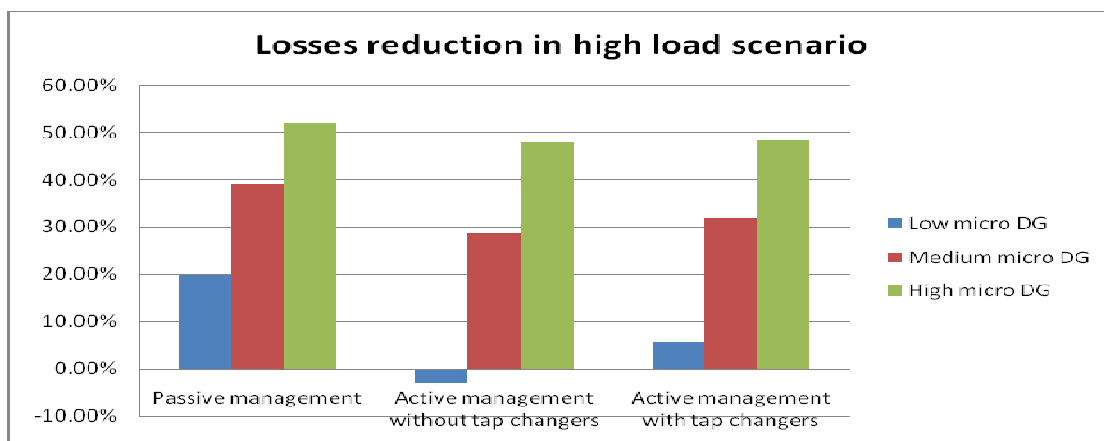


Figure 3.45. Losses reduction in high load scenario.

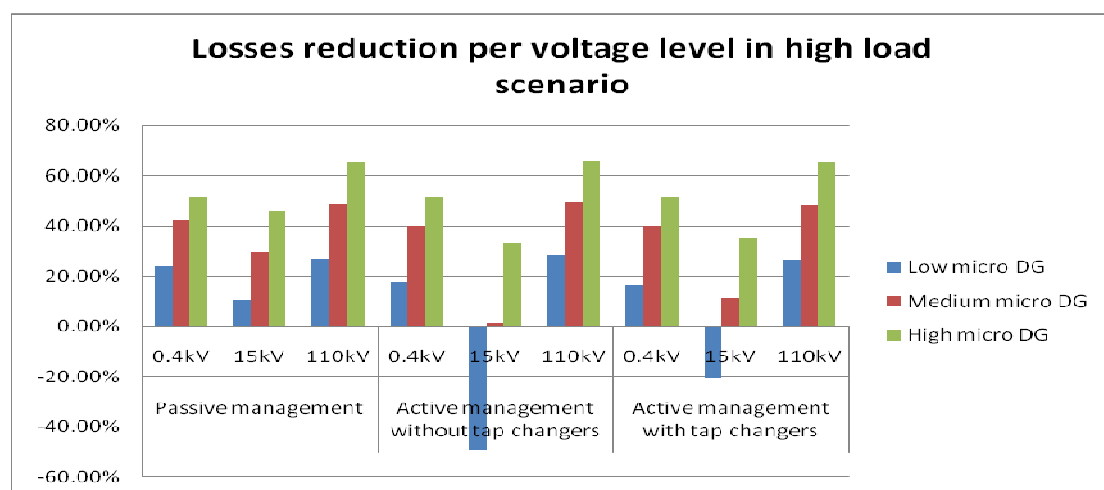


Figure 3.46. Losses reduction per voltage level in high load scenario.

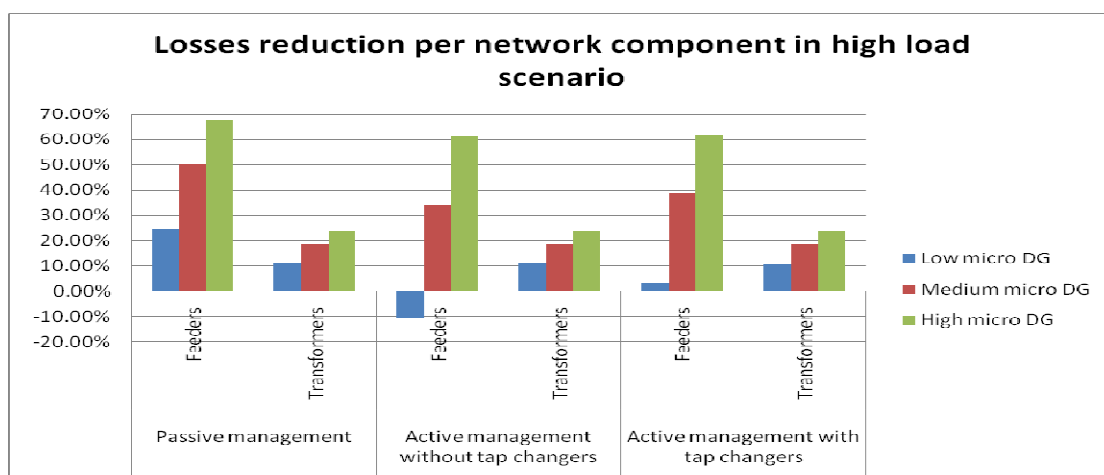


Figure 3.47. Losses reduction per network component in high load scenario.

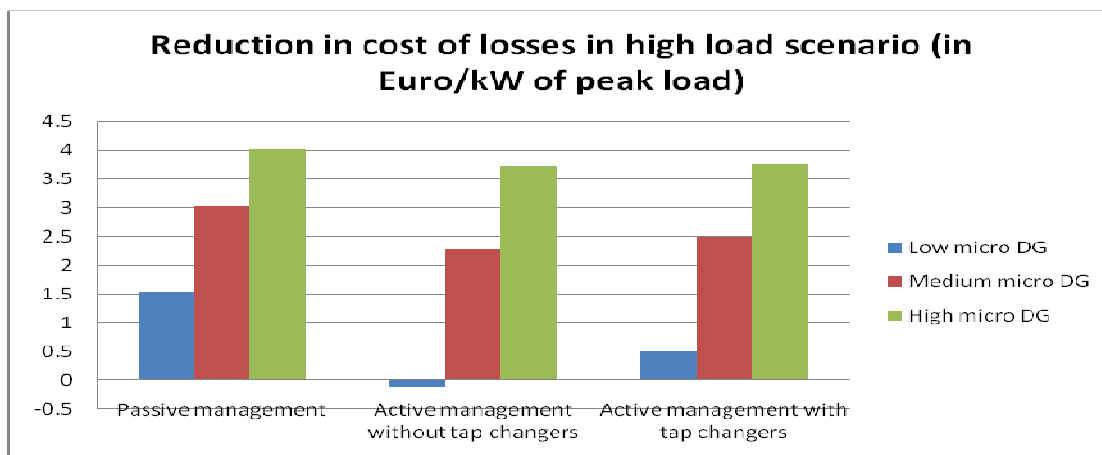


Figure 3.48. Reduction in cost of losses in high load scenario.

### 3.2.4 Benefits Related to Total Network Cost

The reduction in total network cost (sum of the reduction in the annualized reinforcement cost and the reduction in the annual cost of losses) in the low load scenario per kW of peak load is presented in Figure 3.49. We can observe that high micro DG capacity gives the lowest network cost under every strategy because both reinforcement cost and cost of losses are the lowest with this capacity. Moreover, active management gives the lowest network cost in each micro DG penetration scenario (without tap changers in the low and high micro DG scenarios and with tap changers in the medium micro DG scenario); this is due to the fact that even though the cost of losses is lower under passive management, the reinforcement cost is much lower under active management. The same reduction is shown on Figure 3.50 per kW of micro DG installed: we can see that the incremental benefit of micro DG (value of the next kW of micro DG) decreases as its penetration increases since the increase in installed micro DG reduces the available room for the beneficial effects of extra micro DG capacity.

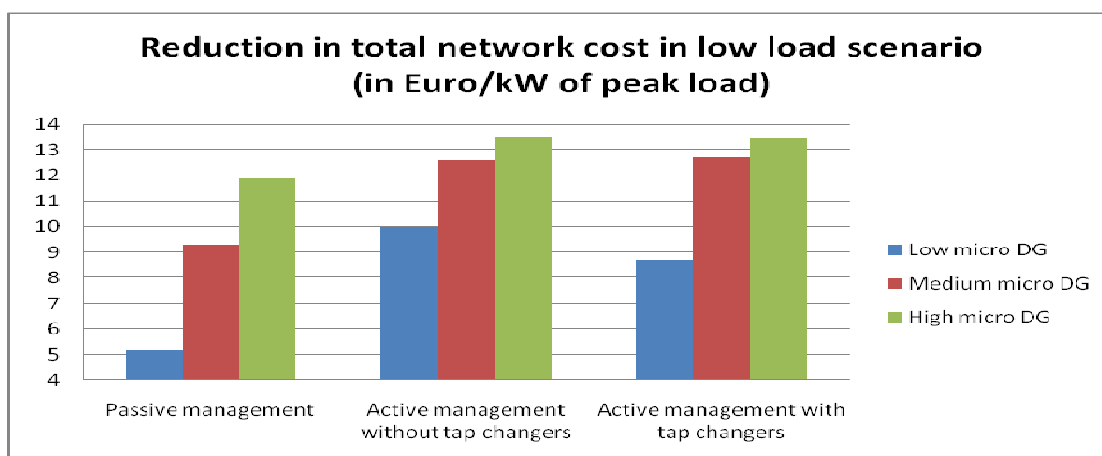


Figure 3.49. Reduction in total network cost in low load scenario (1).

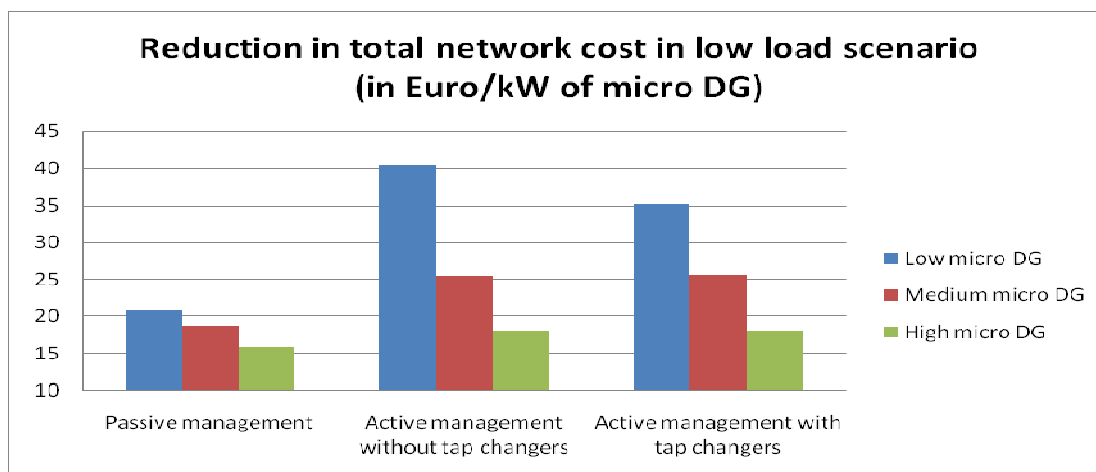


Figure 3.50. Reduction in total network cost in low load scenario (2).

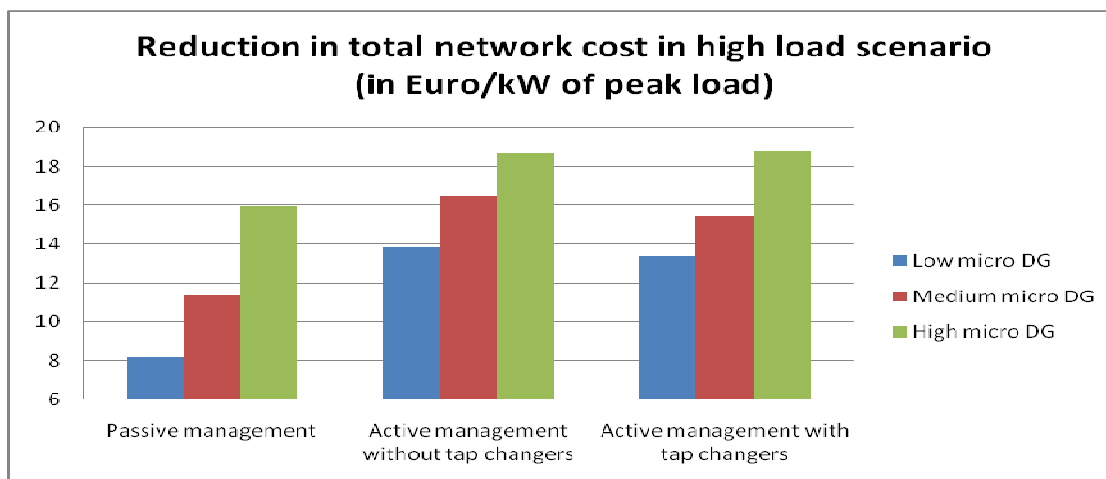


Figure 3.51. Reduction in total network cost in high load scenario (1).

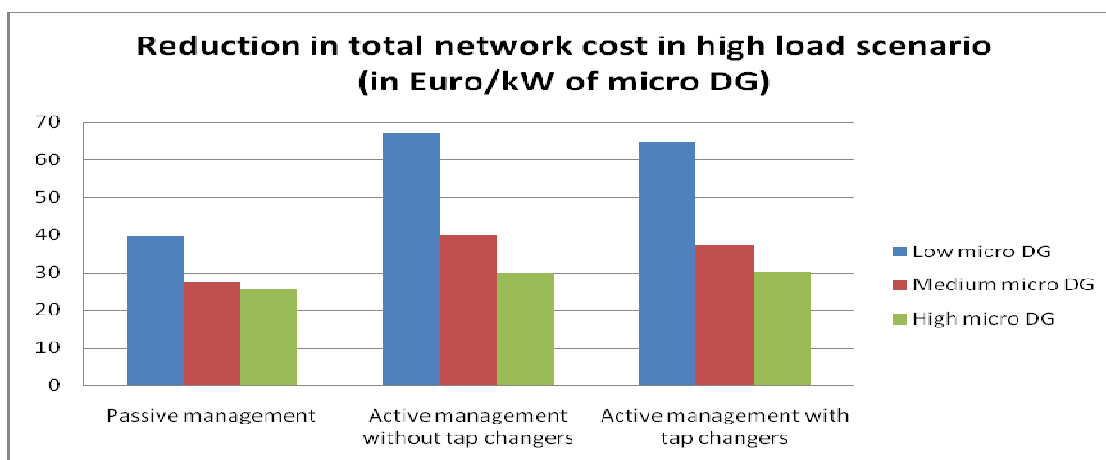


Figure 3.52. Reduction in total network cost in high load scenario (2).

The respective results for the high load case are depicted on Figure 3.51 and Figure 3.52; similar trends to the low load scenario are observed. For a specific micro DG penetration and a specific operating strategy, the incremental benefit of micro DG is much higher in the high load case (compare Figure 3.50 and Figure 3.42), since the increase in demand increases the available room for the beneficial effects of extra micro DG capacity on reinforcement cost and losses.

### 3.2.5 Benefits Related to Local Power Generation

The annual energy production by each type of micro DG in each penetration scenario is found on Figure 3.53; the huge difference in energy production between micro CHP and micro PV is due to: i) their capacity share (60% of the total micro DG capacity is CHP capacity while 40% is PV capacity) and ii) their profiles (the average load factor is much higher for CHP units).

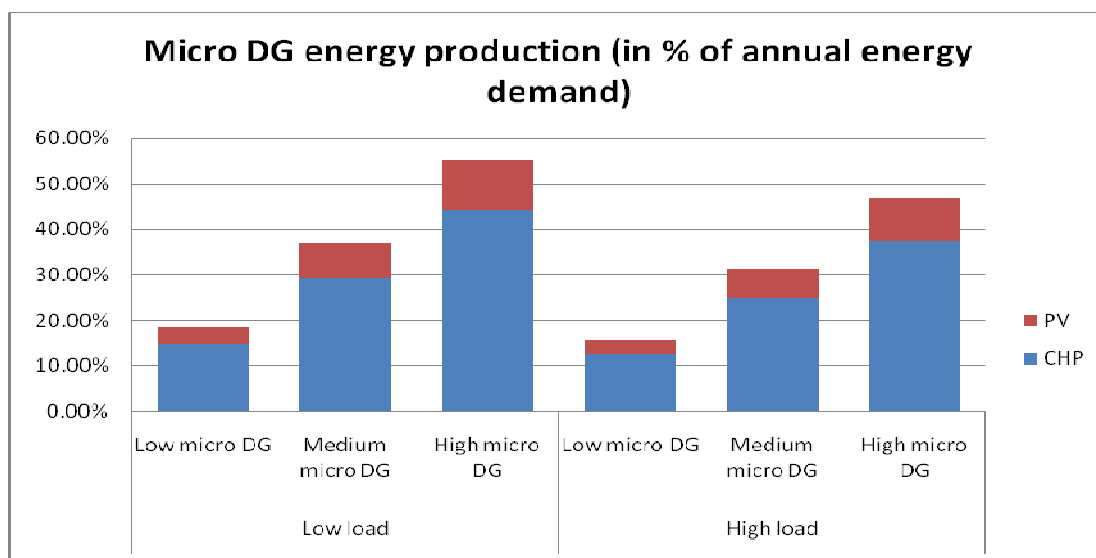


Figure 3.53. Micro DG energy production.

The maximum power flowing on the GSP (boundary between the examined distribution network and the upward transmission network) in the low load scenario (for simplicity reasons only for the optimal operating strategy -the strategy giving the lowest total network cost- in each micro DG scenario) is presented on Figure 3.54. This maximum power flow has a direction from the transmission system to the examined network (power import) in every micro DG scenario; as the micro DG penetration is increased, more of the power required by the load is supplied by local generation and thus the import from transmission is reduced. The observed reduction in the maximum power flow on the GSP is particularly relevant for transmission investment decisions. The same trend is observed in the high load case.

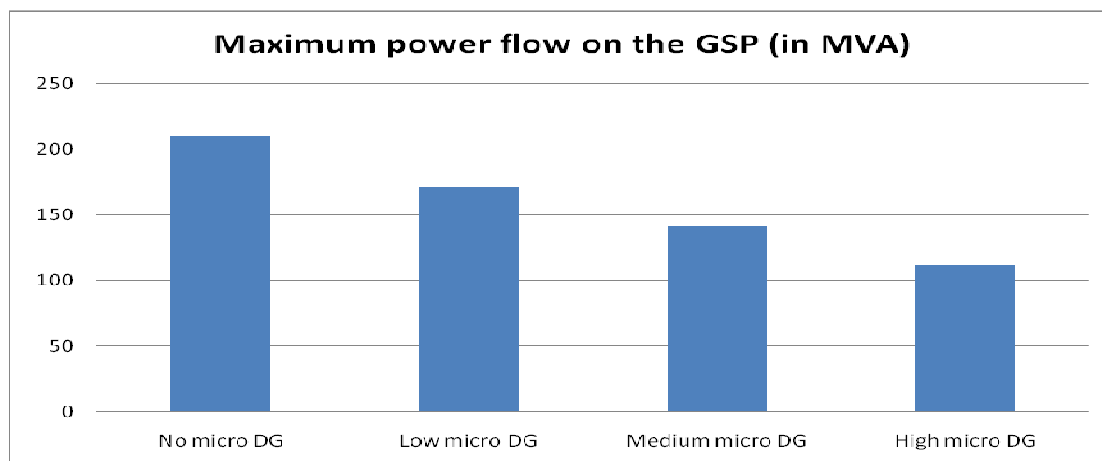


Figure 3.54. Maximum power flow on the GSP.

The hourly profile of the power flowing on the GSP (which expresses the demand curve of the examined distribution network) in a winter weekday (period of highest demand in the network) is depicted on Figure 3.55. The shape of the profile curve is altered by the installation of micro DG: i) the time that the peak occurs is changed (at 13.00 in the no micro DG case, at 14.00 in the low micro DG case and at 22.00 in the medium and high micro DG cases) and ii) the shape of the curve at the time window 8.00-14.00 is modified significantly. These changes in the shape of the profile curve are caused by the PV production at the time window 8.00-14.00. The profile of CHP generators in Poland is flat, so they do not alter the shape of the curve, but they move the whole curve downwards. These results are particularly relevant for central generation scheduling. Same trends are observed in the high load case.

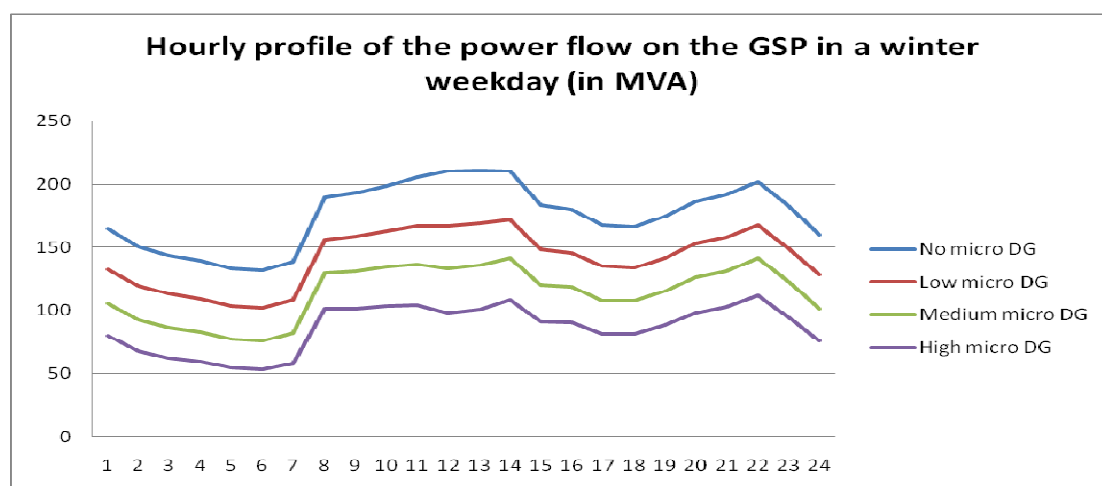


Figure 3.55. Hourly profile of the power flow on the GSP.

### 3.2.6 Environmental Benefits

As explained in detail in the main deliverable, the installation of micro DG results in  $CO_2$  emissions reduction because i) it reduces losses and ii) it displaces part of the central electricity production (micro CHP generators also displace part of the heat production of conventional boilers); the marginal plant model (presented in the main deliverable) and a parametric analysis (for different values of the emission factor of the marginal plant) is used for the calculation of this reduction (for simplicity reasons only for the optimal operating strategy in each micro DG scenario).

The  $CO_2$  emissions reduction (with respect to the no DG case) caused by micro CHP energy production (Figure 3.56), by micro PV energy production (Figure 3.57), by the reduction of losses (Figure 3.58) and the total one (Figure 3.59) for the low load scenario are presented below. We observe that the emissions reduction caused by local power generation (both CHP and PV generation) and losses reduction increases linearly with the emission factor of the marginal plant, as described by the relevant equations in the main deliverable. For a certain emission factor of the marginal plant, the emissions reduction increases with the micro DG capacity (since larger capacity means larger local energy production and larger reduction in losses, as depicted on Figure 3.53 and Figure 3.41 respectively). In every case, the greatest part of the total emissions reduction comes from micro CHP energy production, followed by micro PV energy production. Similar trends are observed in the high load case.

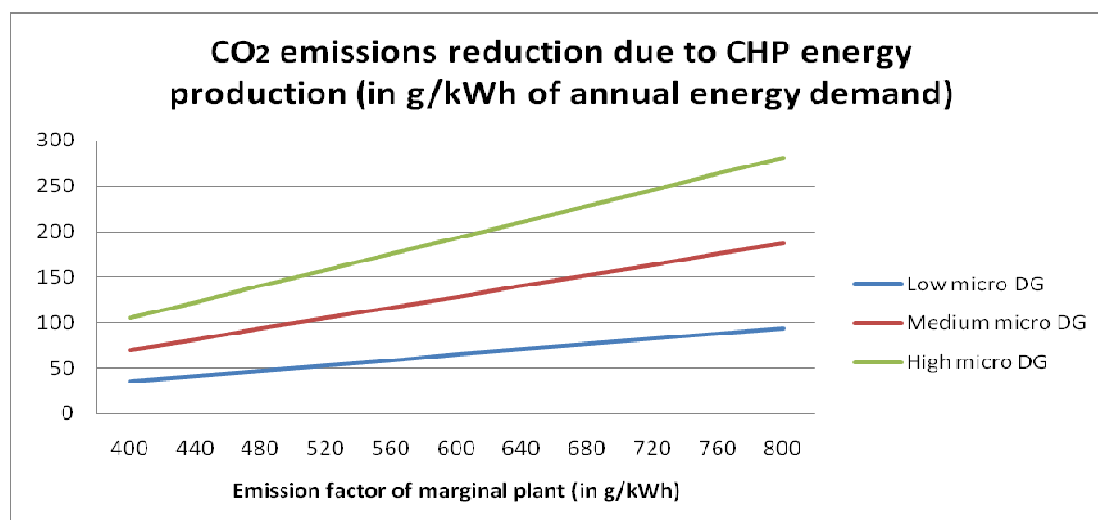


Figure 3.56.  $CO_2$  emissions reduction due to CHP energy production.

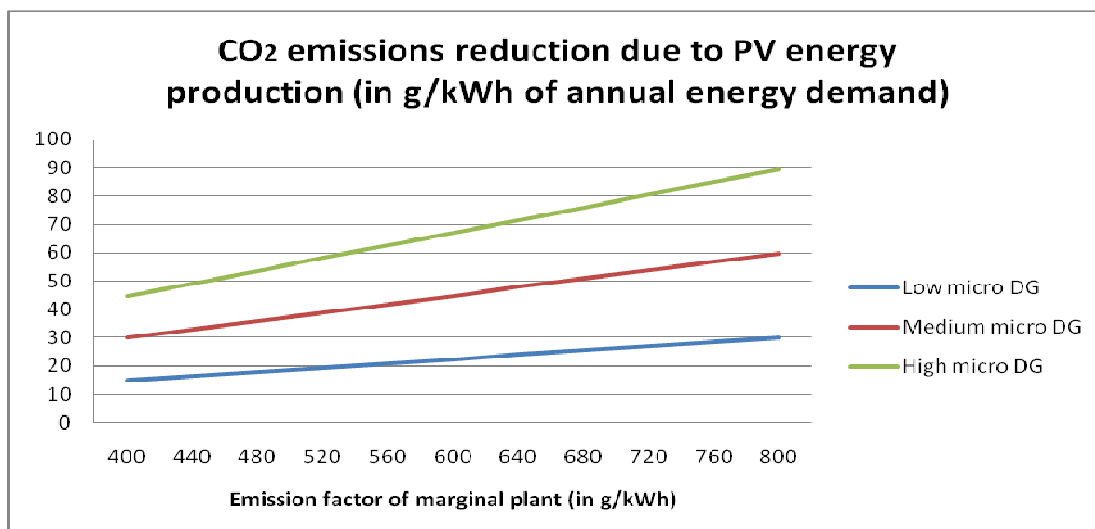


Figure 3.57. CO<sub>2</sub> emissions reduction due to PV energy production.

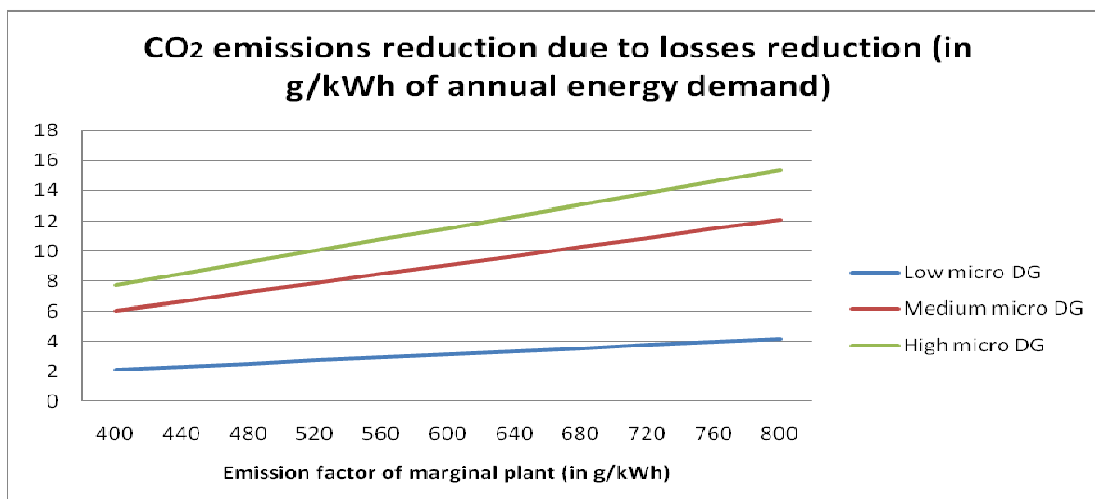


Figure 3.58. CO<sub>2</sub> emissions reduction due to losses reduction.

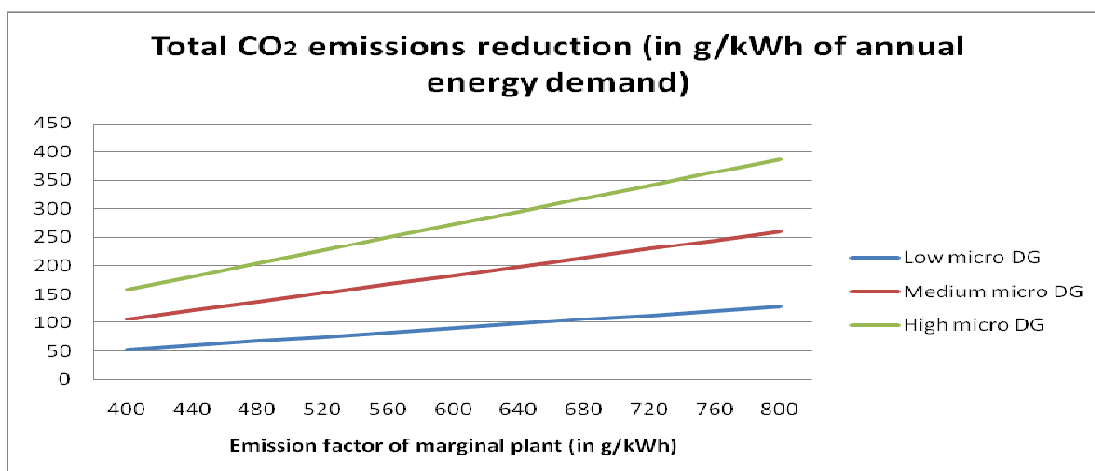


Figure 3.59. CO<sub>2</sub> emissions reduction.

### 3.2.7 Conclusion

Our analysis on the Polish network shows that the whole required **reinforcement** in both low and high load scenarios is related to **violations of voltage limits** caused by demand (voltage drop), with the most severe problems arising at the **medium voltage level**, since it is characterized by many long, overhead lines. Since this reinforcement is driven by demand, the installation of **micro DG reduces reinforcement cost** (Figure 3.37 and Figure 3.39) -by mitigating the above mentioned voltage drop problems- and as the micro DG penetration increases, the reinforcement cost is reduced. It is worth stressing that this beneficial impact of micro DG is not restricted in the voltage level it is connected, as it also extenuates the required reinforcement of higher voltage levels (Figure 3.38 and Figure 3.40). The deployment of **active management reduces further the reinforcement cost**, since the cost of implementing the active controls is much lower than the cost of replacing the feeders suffering from these voltage problems. This benefit of active management becomes less apparent when the micro DG penetration increases and the demand decreases, as the emerging voltage drop problems become less severe. The active management strategy giving the lowest reinforcement cost depends on the relative severity of the emerging voltage problems and consequently on the demand and micro DG combination; from the six possible combinations, active management without tap changers constitutes the least-reinforcement cost option in four (low load-low micro DG, low load-high micro DG, high load-low micro DG and high load-medium micro DG) and active management with tap changers in two (low load-medium micro DG and high load-high micro DG), due to the reasons explained in detail in section 3.2.2.

The installation of **micro DG also reduces losses** at the network (and their cost) as part of the power required by the load is supplied locally and consequently the power flows from the GSP to the demand are reduced (Figure 3.54); thus, as the micro DG penetration increases, the losses reduction with respect to the base case (no DG) becomes more significant (Figure 3.41 and Figure 3.45). **Losses under passive management are lower** because the feeders suffering from voltage problems are replaced with feeders of smaller resistance (which is not the case under active management); moreover, **active management without tap changers is characterized by higher losses** than active management with tap changers: when only capacitive compensation is used for resolving the severe voltage drop problems arising at 15kV feeders, its required capacity is high enough to create significant **reverse power flows** at these feeders (Figure 3.42 and Figure 3.46). These two differences in losses between the different strategies become less apparent as micro DG penetration is increased and load is decreased, since less voltage problems occur and thus less feeders are replaced under passive management and less capacitive compensation is connected at the suffering feeders under active management without tap changers; moreover, since these differences are related to feeders' constraints, they do not affect the transformers' losses significantly (Figure 3.43 and Figure 3.47).

Since micro DG reduces both the reinforcement cost and the cost of losses, it has a **beneficial impact on the total network cost**; as the micro DG penetration increases, the total network cost is reduced (Figure 3.49 and Figure 3.51) since this trend is observed in both reinforcement cost and cost of losses. **Active management reduces further the total network cost**, because its positive impact on the reinforcement cost is much more

significant than its negative impact on the (cost of) losses. The active management strategy giving the lowest total network cost in each demand and micro DG combination is the strategy giving the lowest reinforcement cost for the same combination, since the differences in reinforcement cost between the two strategies (without and with tap changers) are much higher than the respective differences in cost of losses.

The **incremental benefit of micro DG on the total network cost** (value of the next kW of micro DG) decreases as its penetration increases, since the increase in installed micro DG reduces the available room for the beneficial effects of extra micro DG capacity; moreover, for the same micro DG penetration and the same operating strategy, this incremental benefit is higher in the high load scenario, since the emerging voltage drop problems are more severe and thus there is more room for beneficial effects of extra micro DG (Figure 3.50 and Figure 3.52).

Due to the fact that the foreseen capacity share of micro CHP generators is higher than the respective share of micro PV generators and the average load factor of the former is much higher, the **micro CHP energy production is much higher** than the micro PV energy production (Figure 3.53). The installation of these two types of **micro DG alters the aggregate demand curve of the polish distribution network** (Figure 3.55). Micro CHP generators do not change the shape of the curve, but just move it downwards, since their generation profile is flat; micro PV generators on the other hand alter significantly the shape of the curve (as a result the time that the peak demand occurs in a winter weekday is changed) due to the characteristics of their generation profile (they only produce energy in morning and early afternoon).

Finally, **micro DG reduces CO<sub>2</sub> emissions** since it reduces losses and it displaces part of the central electricity production (micro CHP generators also displace part of the heat production by conventional boilers). For a certain emission factor of the marginal plant of central generation, the emissions reduction with respect to the base case (no DG) increases with the micro DG penetration, as the losses reduction and the micro DG energy production become more significant (Figure 3.56 to Figure 3.59). The most significant component of emissions reduction comes from the displacement of conventional boilers' heat and central electricity production by the energy production of micro CHP generators.

## 4. Distribution Network Analysis for Netherlands

### 4.1 Dutch Scenarios

#### 4.1.1 General Information

The total peak load for an average GSP (there are 300 GSPs in the Netherlands) is estimated to be equal to 66 MW, with breakdown by voltage level given in Table 4.1. The load growth given is 2% per annum. Basic network information is given in Table 4.2. The DG penetration levels for 2010, 2015, 2020 and 2030 are shown in Figure 4.1. In addition, Figure 4.2 shows the breakdown by voltage level for the different DG types.

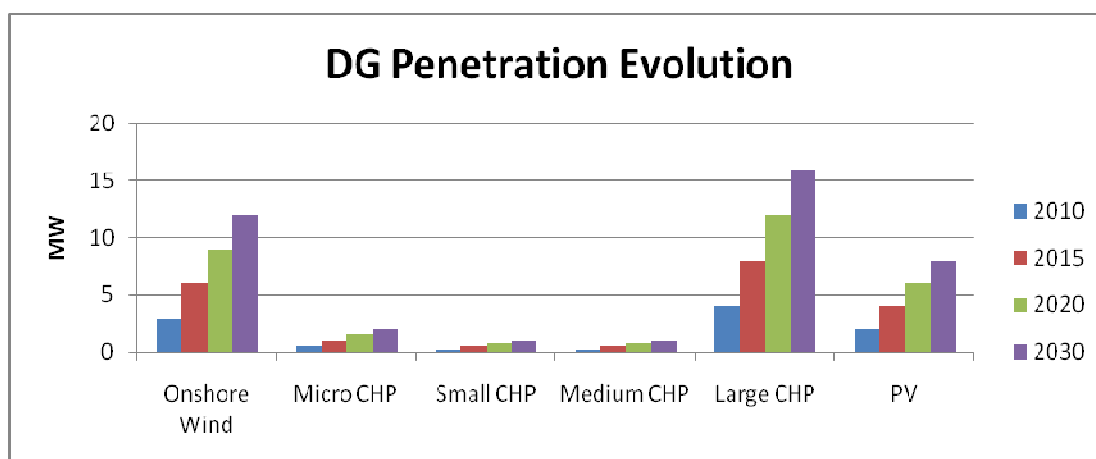


Figure 4.1. Basic penetration evolution.

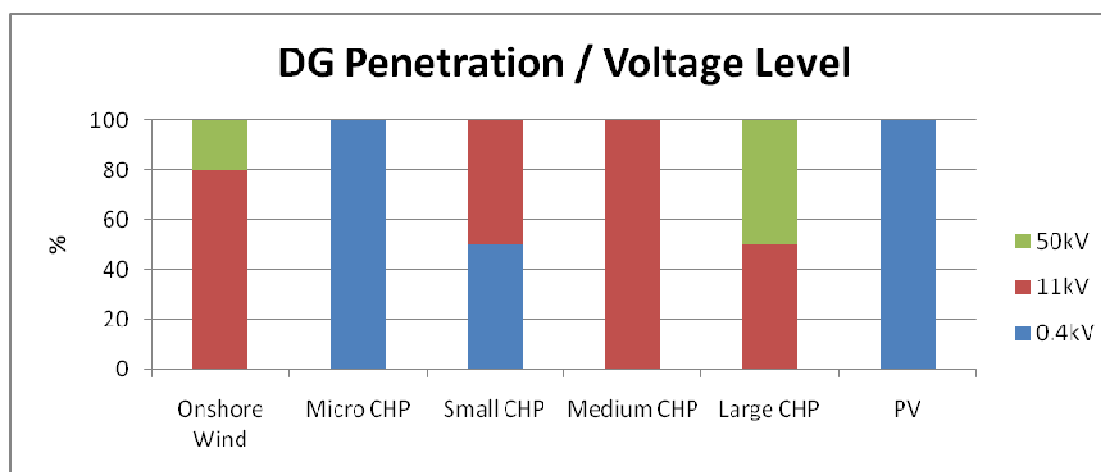


Figure 4.2. DG penetration per voltage level.

<b>Maximum load in GSP</b>	66 MW	100%
<b>Maximum load at 0.4kV</b>	26.4 MW	40%
<b>Maximum load at 11kV</b>	19.8 MW	30%
<b>Maximum load at 50kV</b>	13.2 MW	20%
<b>Maximum load at 150kV</b>	6.6 MW	10%

Table 4.1. Maximum load per voltage level

<b>Voltage level</b>	0.4 kV	11 kV	50 kV	150 kV
<b>Number of model types</b>	4	4	1	1
<b>Number of each model type per GSP</b>	250 for each model	Model 1: 4	4	1
		Model 2: 4		
		Model 3: 8		
		Model 4: 8		
<b>Number of total modules per GSP</b>	1000	24	4	1
<b>Number of circuits per model</b>	Model 1: 2	Model 1: 8	6	4
	Model 2: 2	Model 2: 8		
	Model 3: 4	Model 3: 8		
	Model 4: 4	Model 4: 8		
<b>Total number of circuits</b>	3000	192	24*2=48	4*2=8
<b>Total number of transformers</b>	1000	24*2=48	4*2=8	1*2=2
<b>Capacity of transformers / models (MVA)</b>	Model 1: 0.1	Model 1: 7.5*2	66*2	240*2
	Model 2: 0.25	Model 2: 17.5*2		
	Model 3: 0.25	Model 3: 7.5*2		
	Model 4: 0.63	Model 4: 17.5*2		

Table 4.2. Structure of the Dutch distribution network

#### 4.1.2 Benefits Related to Losses

Figure 4.3 shows the total reduction in network losses after the introduction of DG. In addition, Figure 4.4 presents the total losses reduction per voltage level after introduction of DG and Figure 4.5 shows the reduction in transformer and circuit losses. It should be stressed that negative reduction is equivalent to an increase. It is evident that introduction of DG significantly increases total network losses. Although losses are reduced at 0.4 kV, 50 kV and 150 kV, losses at 11 kV increase. Furthermore, although transformer losses are not affected significantly, circuit losses increase dramatically. This can be attributed

to reverse power flows at 11 kV because of the relatively large size of DG in comparison to the corresponding circuit’s load. This increase in losses becomes more significant in the future, as the DG penetration increases faster than the demand.

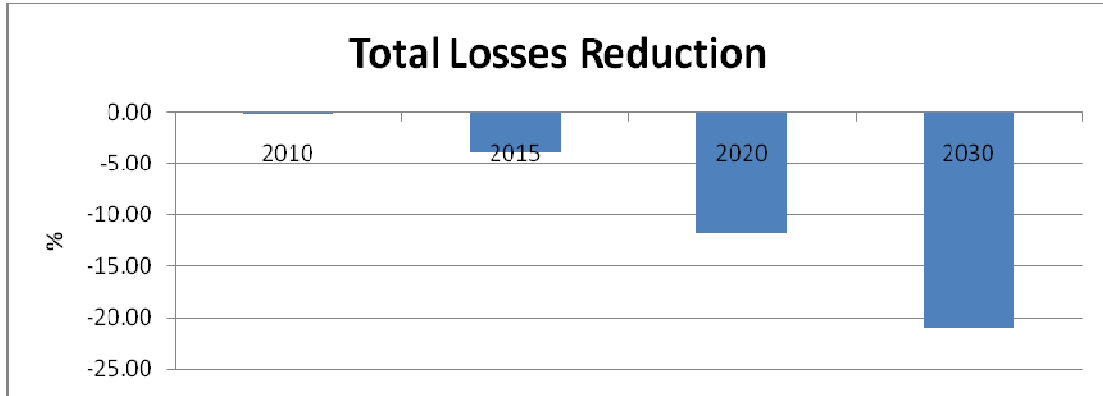


Figure 4.3. Total losses reduction after introduction of DG.

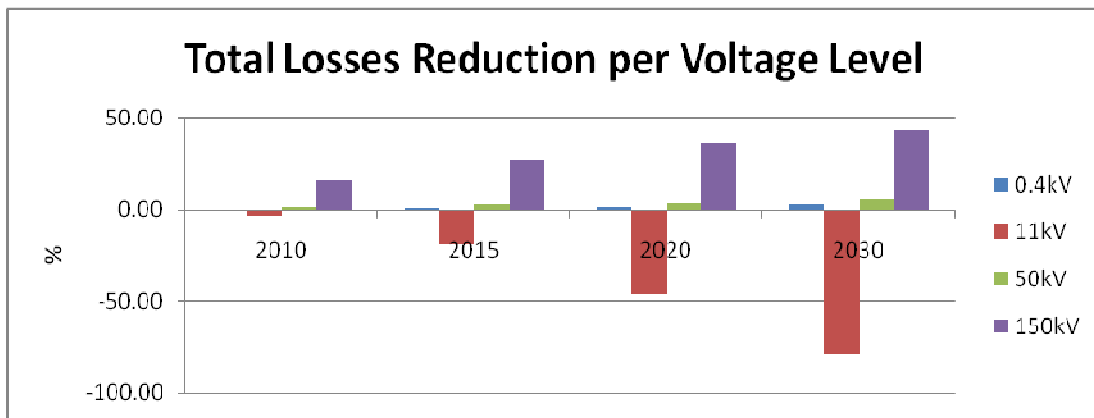


Figure 4.4. Losses reduction per voltage level after introduction of DG.

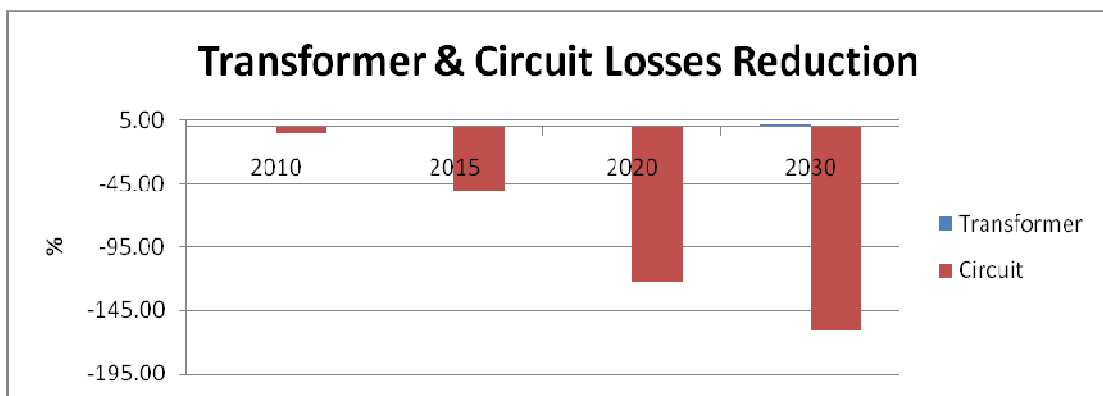


Figure 4.5. Reduction of transformer and circuit losses after introduction of DG.

Figure 4.6 presents a parametric analysis of avoided grams of CO<sub>2</sub> per kWh<sub>e</sub> of energy consumed annually coming from the marginal plant as a function of the emission factor (grams of CO<sub>2</sub> per kW<sub>e</sub> produced) of the marginal plant thanks to losses reduction. As expected, because of the increase in total losses, there are additional CO<sub>2</sub> emissions. Finally, Figure 4.7 quantifies the financial benefit of total losses reduction in €/MW<sub>peak</sub> assuming 3% inflation and 7% discount rate. Once again, because of the increase in total losses, there is a financial loss rather than a financial benefit.

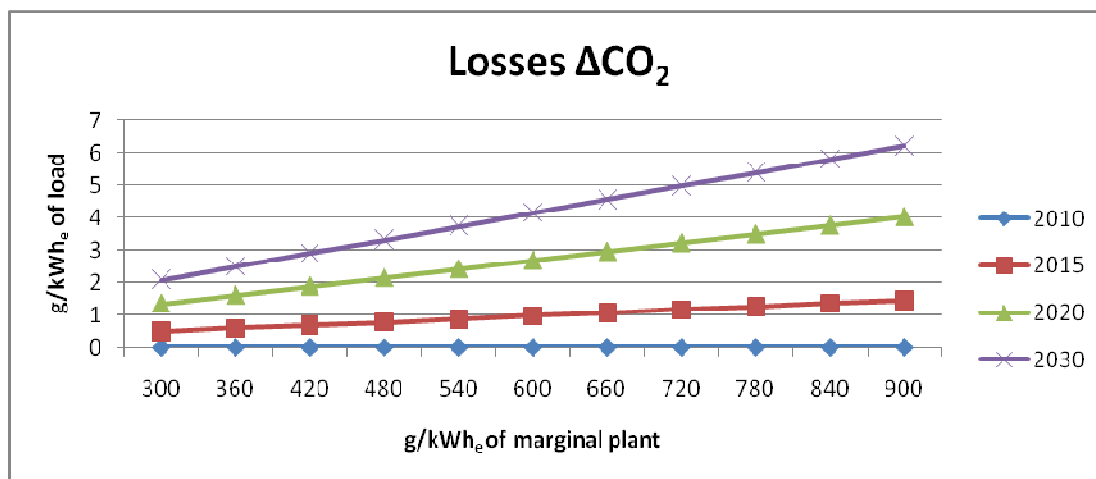


Figure 4.6. Environmental benefit from losses reduction.

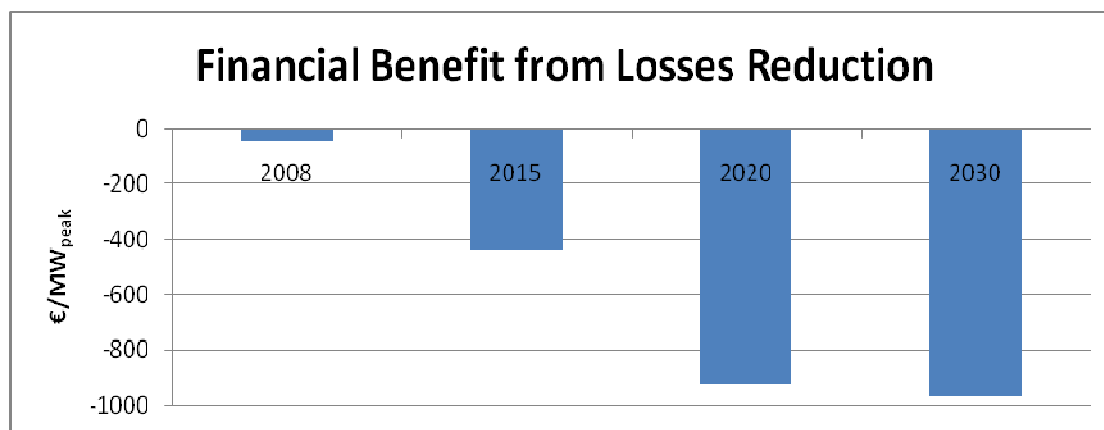


Figure 4.7. Financial benefit from losses reduction.

### 4.1.3 Reinforcement Requirements

The network operates within voltage and thermal limits for all DG penetration scenarios. In addition, reinforcement due to increased short circuit level is not likely.

#### 4.1.4 Benefits Related to Local Power Generation

One of the most significant contributions of power generation using DG (RES and CHP) is reducing CO<sub>2</sub> emissions coming from central conventional marginal plant. Figure 4.8 presents the total avoidance of CO<sub>2</sub> emissions thanks to power generation from DG. Figure 4.9 presents the total energy produced by local generation per kWh of demand.

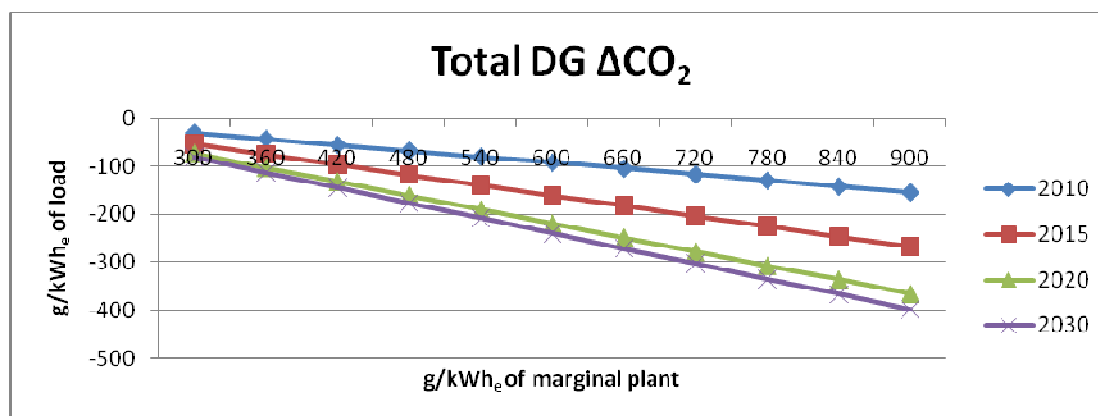


Figure 4.8. Parametric analysis of Total DG ΔCO<sub>2</sub>.

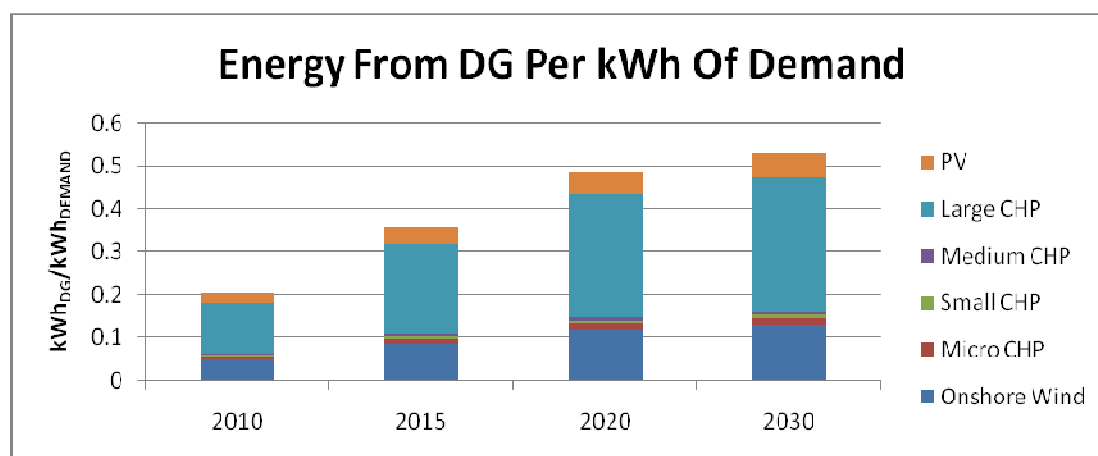


Figure 4.9. Energy from DG per kWh of demand.

#### 4.1.5 Total Environmental Benefit

Figure 4.10 presents the total avoided CO<sub>2</sub> emission from DG, taking into consideration both power generation (RES and CHP) and losses. It has to be noted that although total losses increase, penetration of DG is beneficial in terms of CO<sub>2</sub> emissions thanks to local power generation and avoidance of CO<sub>2</sub> emissions from the marginal plant of the system.

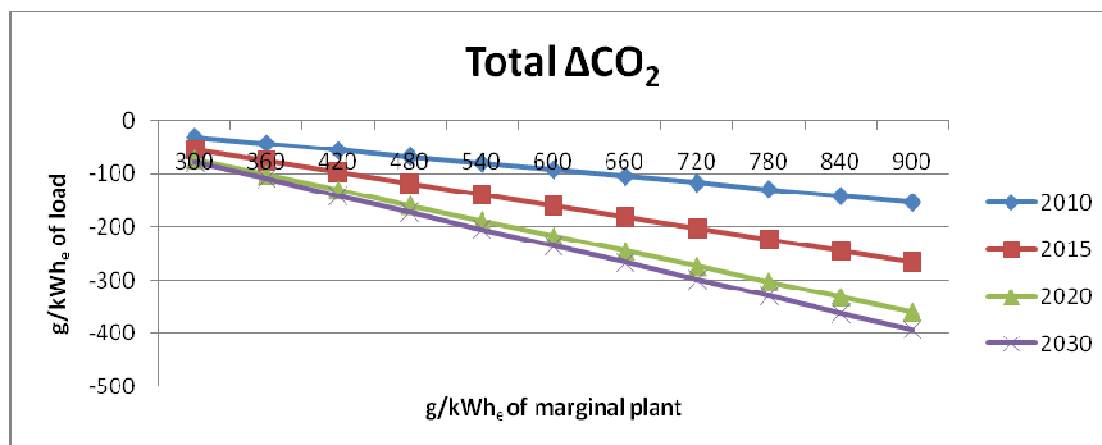


Figure 4.10. Parametric analysis of Total ΔCO<sub>2</sub>.

#### 4.1.6 Benefits Related to Total Network Cost

As there is no need for network reinforcement, the total network cost is increased by the amount coming from total losses increase.

#### 4.1.7 Benefits Related to GSP Power Flows

Figure 4.11 presents the maximum GSP power flows with and without DG. In both cases, the maximum GSP power flow increases. On the other hand, in the presence of DG, the rate of increase is lower. Figure 4.12 shows the GSP power flow for a winter weekday, with and without DG for 2030. It can be seen that the GSP power flow is considerably lower with DG and, in addition, the peak power flow occurring at 18:00 is roughly 20 MW lower.

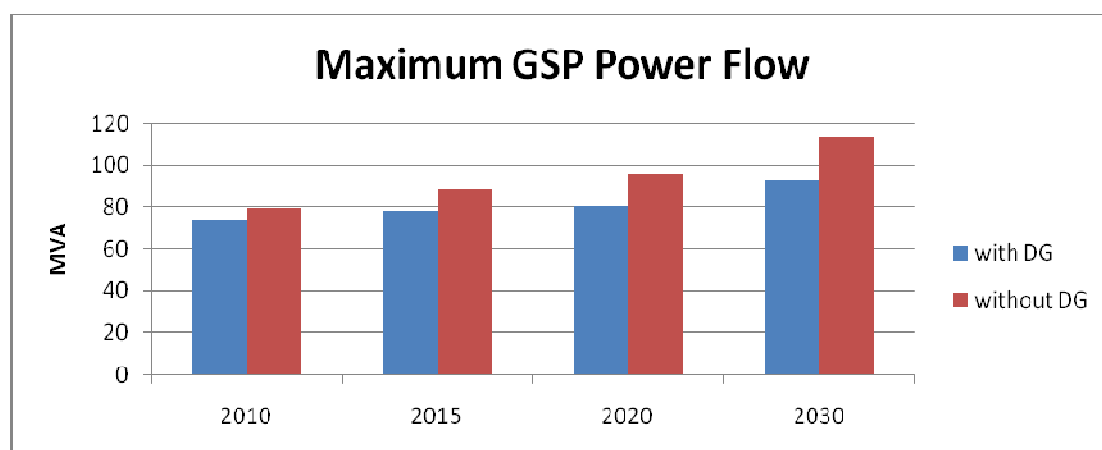


Figure 4.11. Maximum GSP power flow.

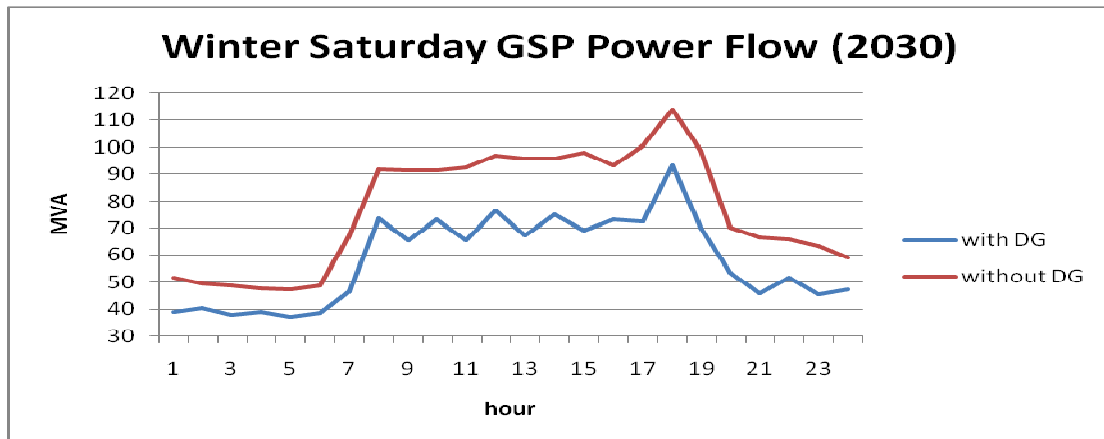


Figure 4.12. Winter weekday GSP power flow (2030).

#### 4.1.8 Conclusion

The Dutch network is able to accommodate the envisaged DG penetration evolution **without thermal, voltage and short circuit level problems**.

Total losses increase with the installation of DG and this increase becomes more significant throughout the years, as the DG penetration increases faster than the demand. It is noted that circuit losses increase dramatically compared to transformer losses, revealing reverse power flows because of increased DG penetration in circuits with relatively low demand.

In terms of CO<sub>2</sub> emissions, local power generation from CHP and RES results in **significant reduction in CO<sub>2</sub> emissions** thanks to avoided emissions from the marginal plant of the system. The increase in total losses only marginally decreases the environmental benefits.

Overall, **network cost increases** because of increased losses.

Finally, **DG penetration decreases the maximum GSP power flows** with potential benefits coming from deferral of transmission system investments.

## 4.2 MicroGrid Scenarios

### 4.2.1 General Information

The same Dutch network was used to examine the impact of Micro DG. For this, the 2010 maximum load per voltage level was considered to be the base load and two LV load growth cases were examined: +10% and +50% of the 2010 LV load. In terms of Micro DG penetration, four cases were considered: 0%, 50%, 100% and 150% of the 2010 LV load. Figure 4.13 shows the LV load growth scenarios and Figure 4.14 shows the Micro DG penetration scenarios. In all cases, the load in the rest of the voltage levels

was considered fixed and equal to the one in the 2010 case. Only Micro CHP and PV were considered as Micro DGs, with 60% and 40% share of the total Micro DG capacity, respectively.

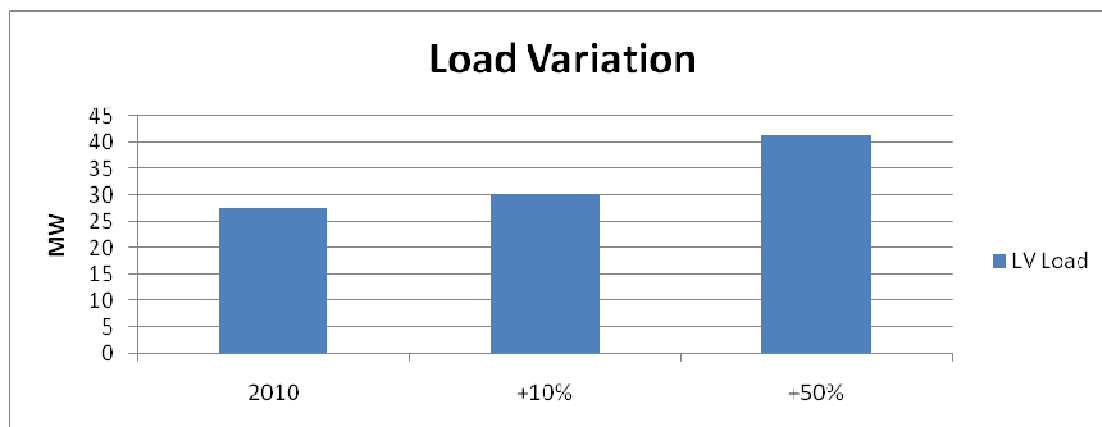


Figure 4.13. LV load growth scenarios.

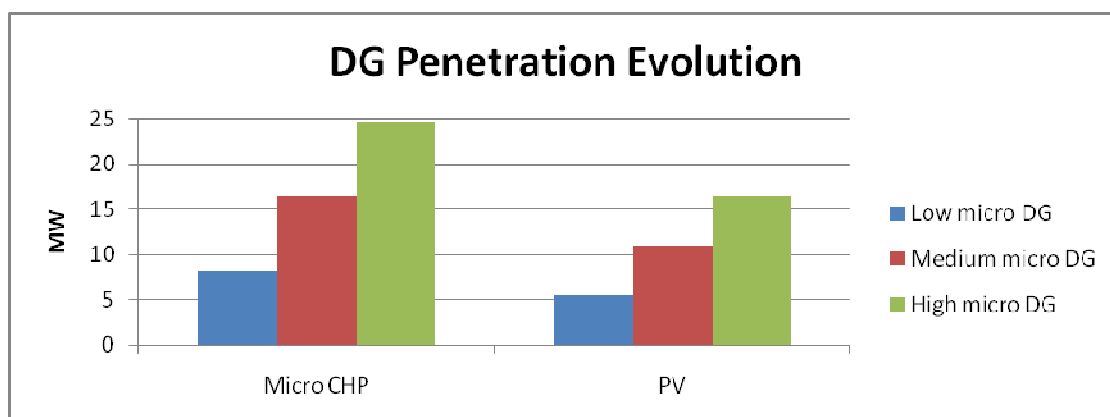


Figure 4.14. Micro DG penetration evolution scenarios.

#### 4.2.2 Benefits Related to Losses

Figure 4.15 shows the total reduction in network losses after the introduction of Micro DG. As Micro DG penetration increases the losses reduction increases. Figure 4.16 presents the total losses reduction per voltage level after the introduction of Micro DG. It is noted that losses reduce at all voltage levels. Figure 4.17 shows the reduction in transformer and circuit losses. It is obvious that the benefit of Micro DG mainly comes from the reduction of circuit losses. Transformer losses also decrease but not as profoundly as circuit losses.

Figure 4.18 and Figure 4.19 present a parametric analysis of avoided grams of CO<sub>2</sub> per kWh<sub>e</sub> of energy consumed annually coming from the marginal plant as a function of the

emission factor of the marginal plant. Finally, Figure 4.20 quantifies the financial benefit of total losses reduction in €/MW<sub>peak</sub>.

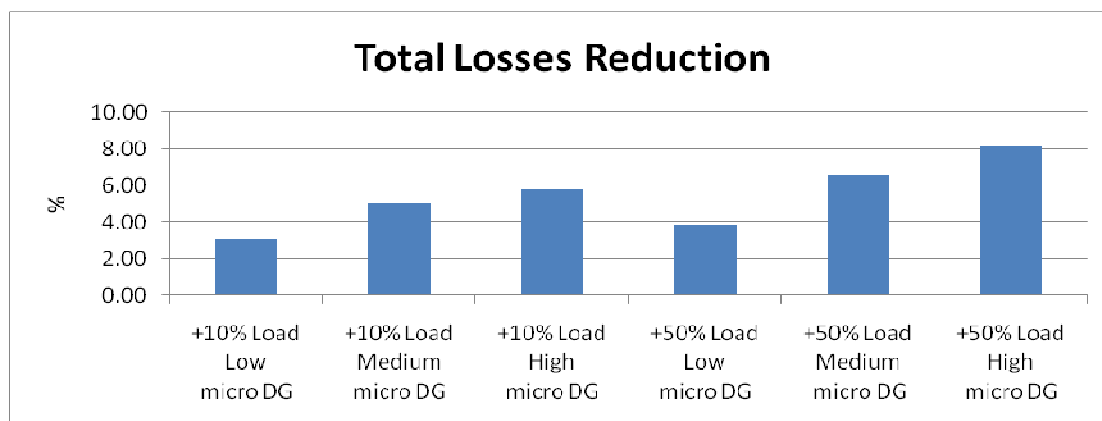


Figure 4.15. Total losses reduction after introduction of Micro DG.

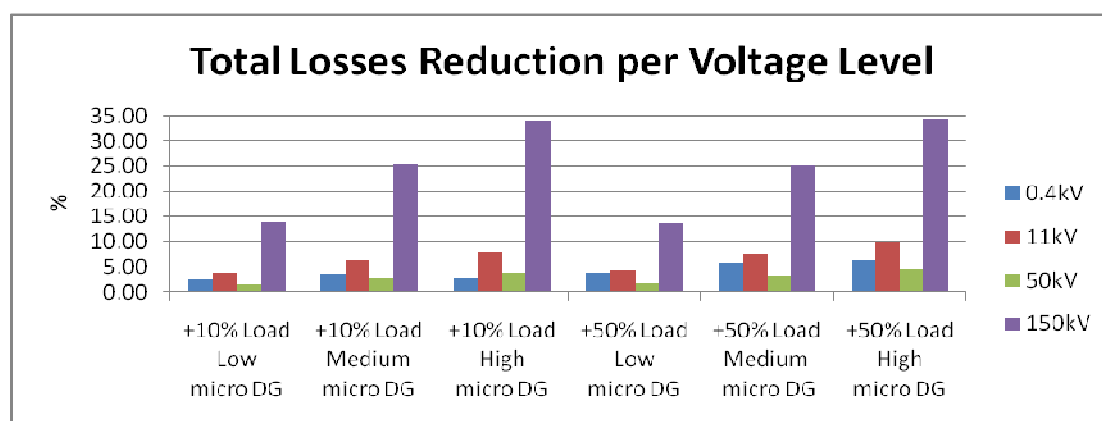


Figure 4.16. Losses reduction per voltage level after introduction of DG.

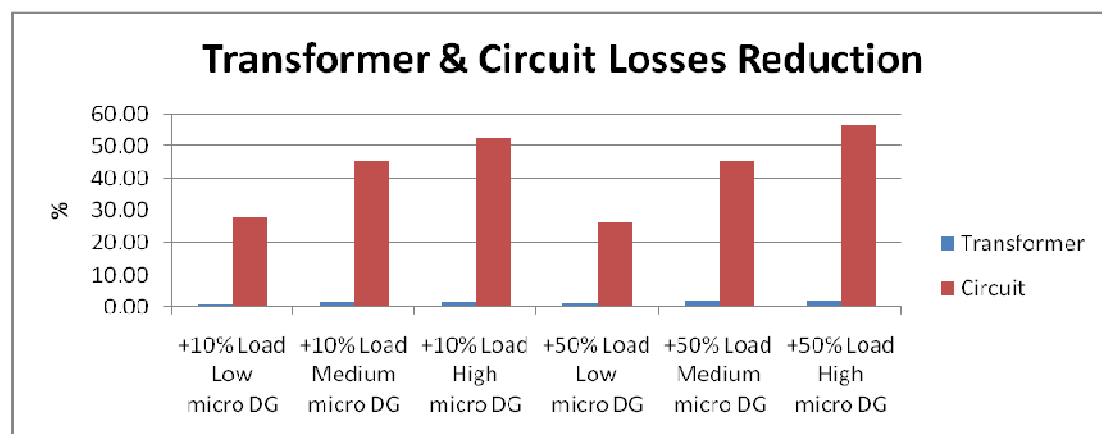


Figure 4.17. Total circuit and transformer losses / demand with DG.

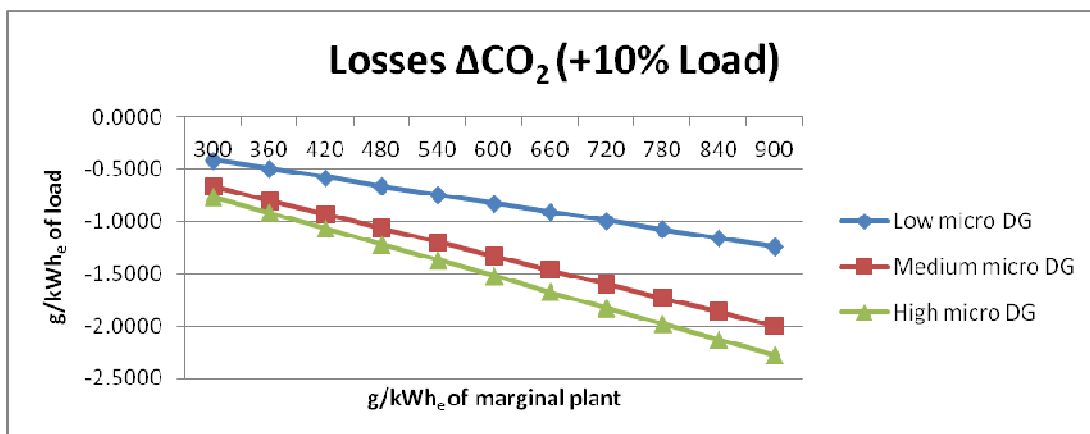


Figure 4.18. Environmental benefit from losses reduction (+10% load).

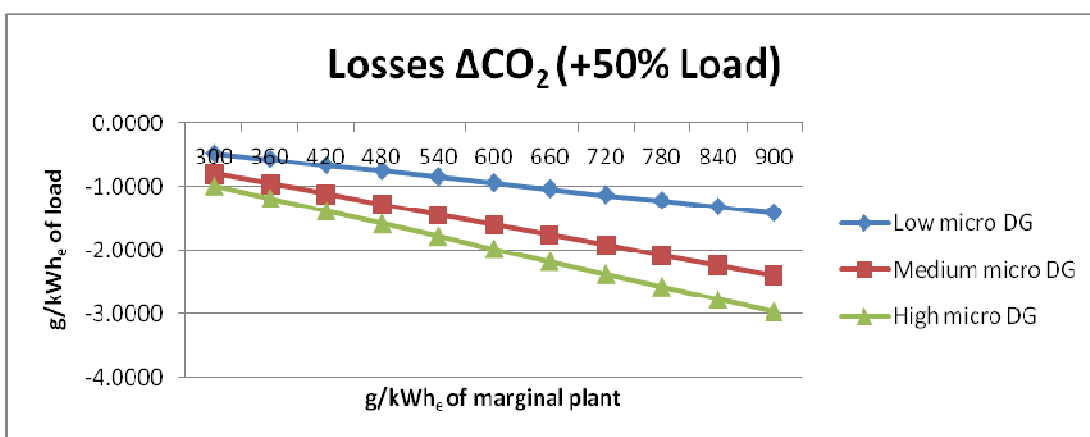


Figure 4.19. Environmental benefit from losses reduction (+50% load).

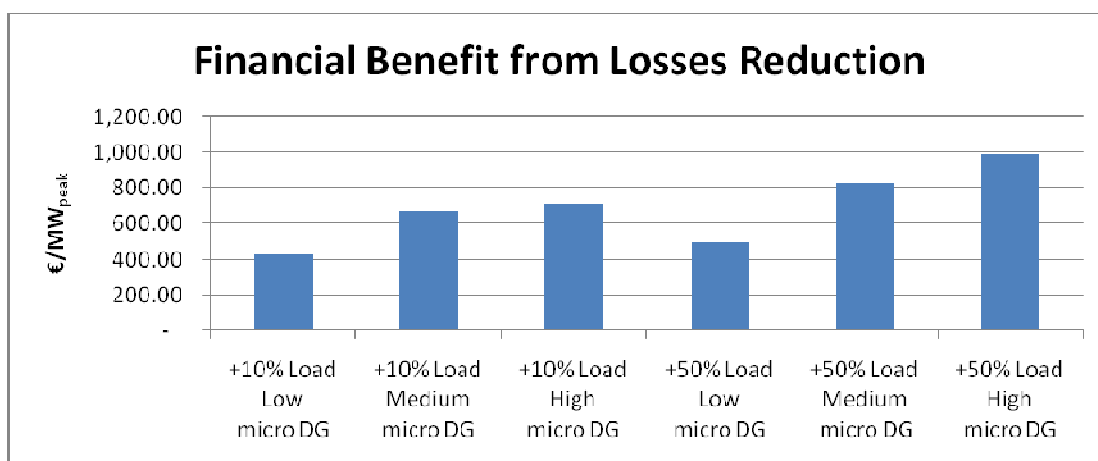


Figure 4.20. Financial benefit from losses reduction.

### 4.2.3 Reinforcement Requirements

The network operates within voltage and thermal limits for all DG penetration scenarios. In addition, reinforcement due to increased short circuit level is not likely.

### 4.2.4 Benefits Related to Local Power Generation

Figure 4.21 and Figure 4.22 present the total avoidance of CO<sub>2</sub> emissions thanks to power generation from Micro DG. Finally, Figure 4.23 and Figure 4.24 present the total energy produced by local generation per kWh of demand for 10% and 50% load increase, respectively.

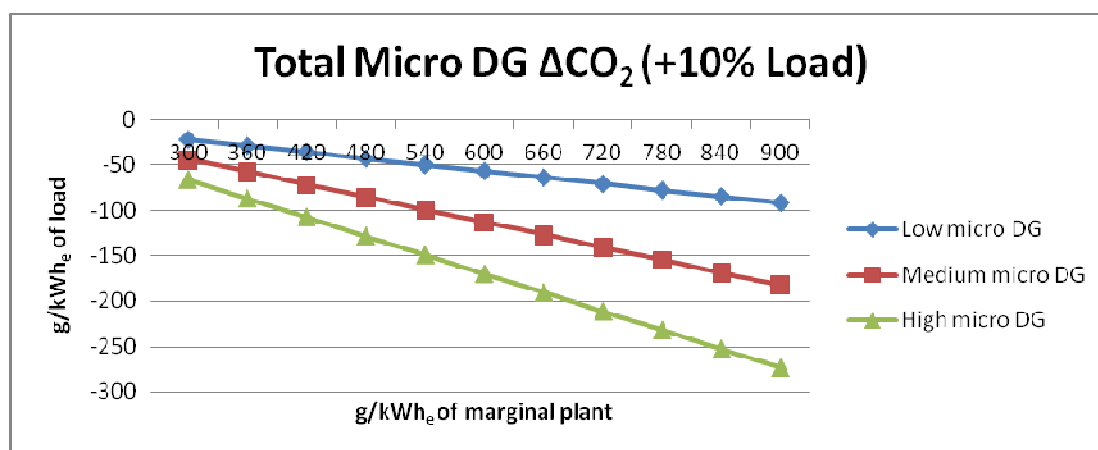


Figure 4.21. Parametric analysis of total Micro DG ΔCO<sub>2</sub> (+10% load).

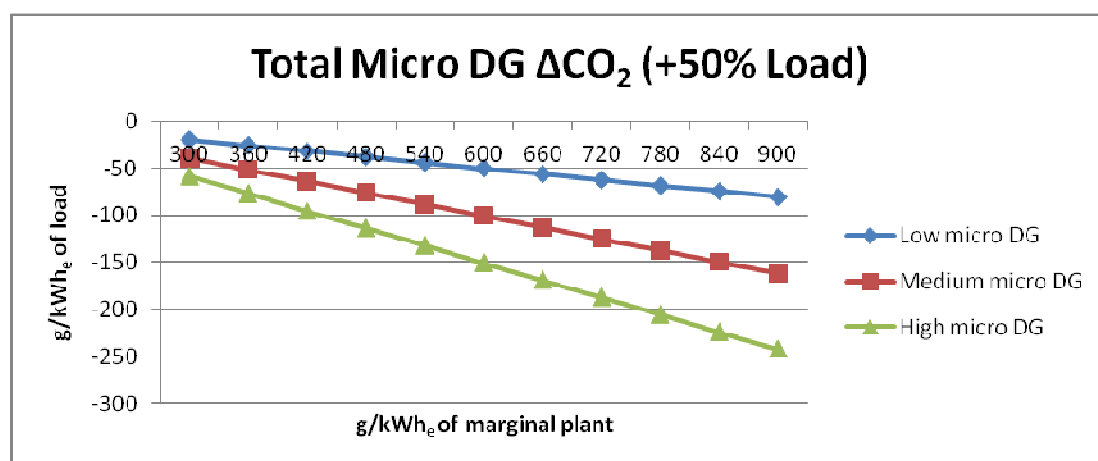


Figure 4.22. Parametric analysis of total Micro DG ΔCO<sub>2</sub> (+50% load).

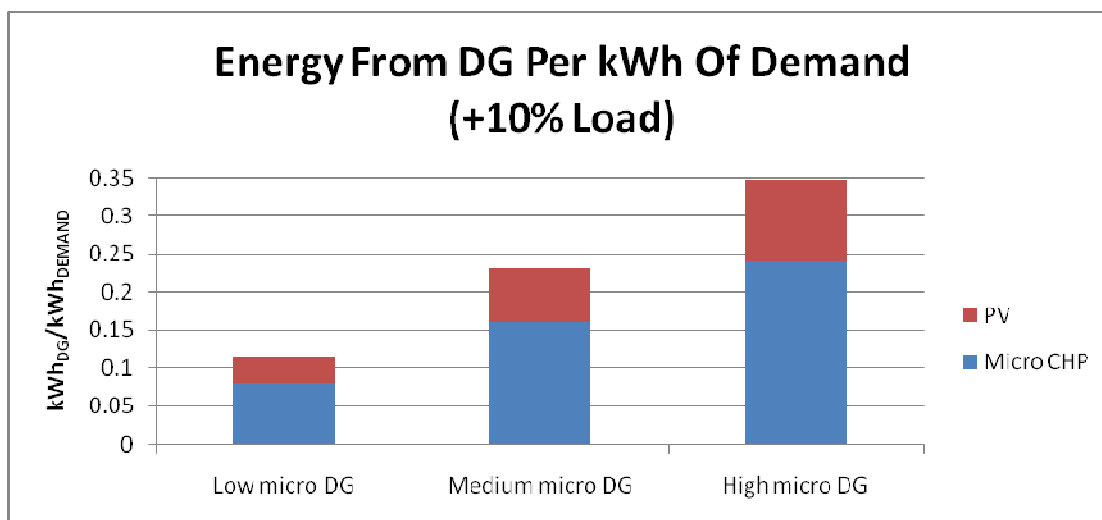


Figure 4.23. Energy from Micro DG per kWh of demand (+10% load).

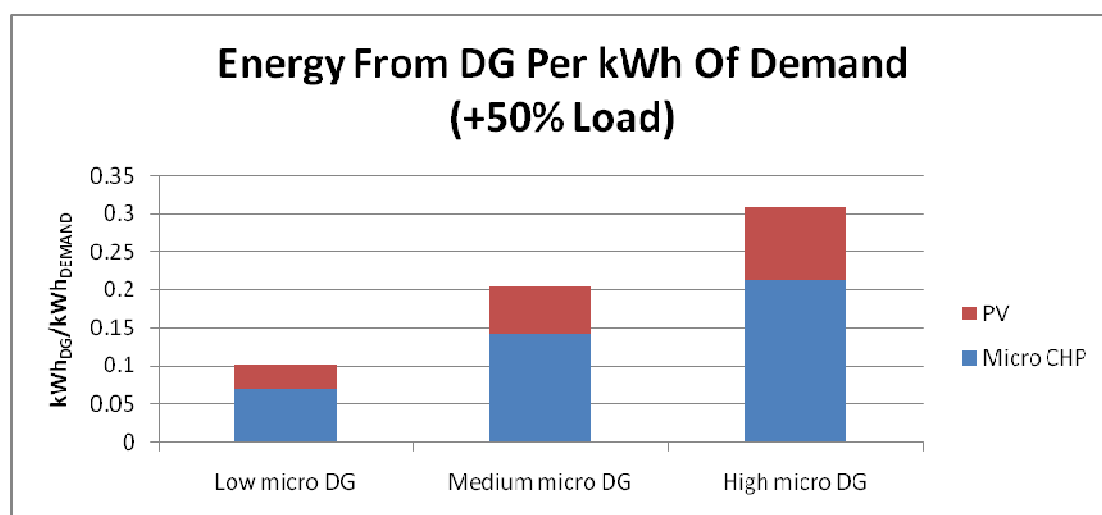


Figure 4.24. Energy from Micro DG per kWh of demand (+50% load).

#### 4.2.5 Total Environmental Benefit

Figure 4.25 and Figure 4.26 present the total avoided CO<sub>2</sub> emission from Micro DG, coming from both power generation (Micro CHP and PV) and losses reduction. It has to be noted that the majority of benefit is coming from power generation, with reduction of losses having only a small contribution in the total CO<sub>2</sub> emissions reduction.

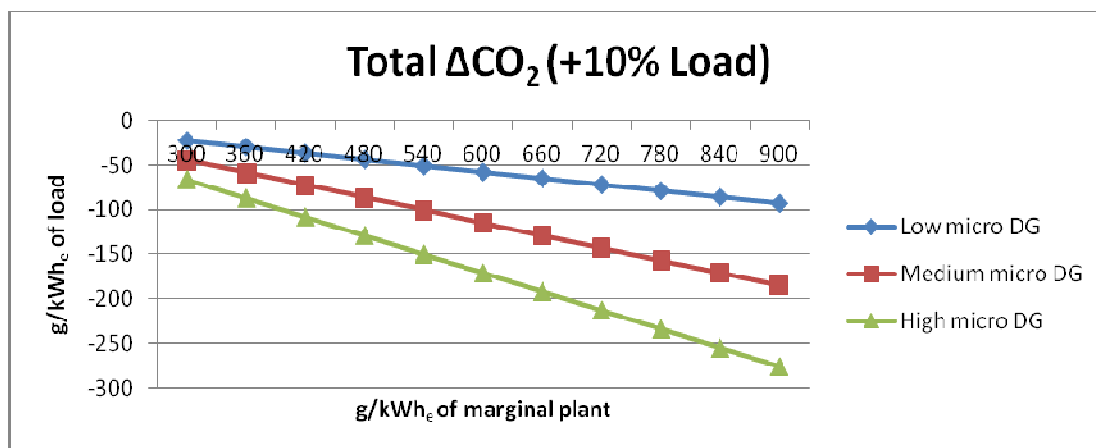


Figure 4.25. Parametric analysis of Total ΔCO<sub>2</sub> (+10% load).

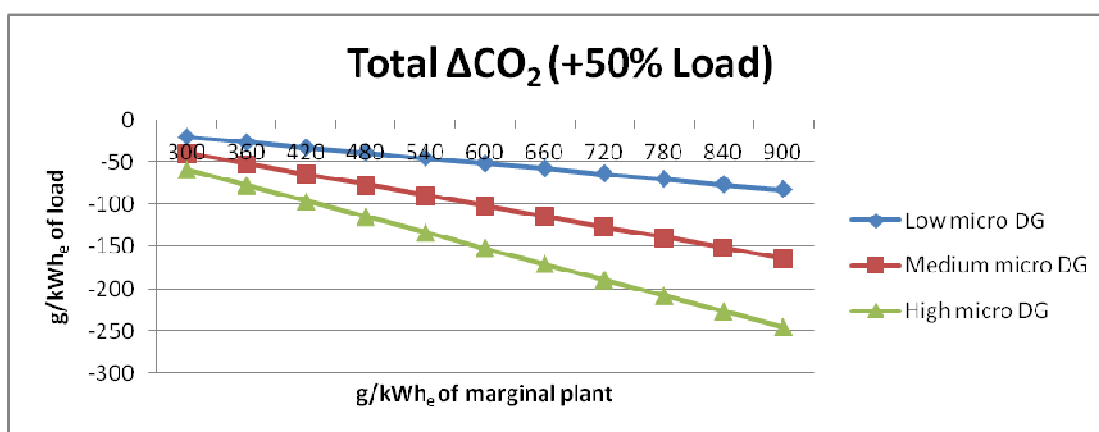


Figure 4.26. Parametric analysis of Total ΔCO<sub>2</sub> (+50% load).

#### 4.2.6 Benefits Related to Total Network Cost

As there is no need for network reinforcement, the total network cost is reduced by the amount coming from total losses reduction.

#### 4.2.7 Benefits Related to GSP Power Flows

Figure 4.27 presents the maximum GSP power flows with and without Micro DG. The maximum GSP power flow is steadily decreasing with increasing Micro DG penetration. Figure 4.28 and Figure 4.29 show the GSP power flow for a winter weekday, with and without Micro DG. It is noted that Micro DG, apart from reducing the maximum GSP power flow, change the time of peak occurrence.

#### 4.2.8 Conclusion

The Dutch network is able to accommodate the envisaged Micro DG penetration **without thermal, voltage and short circuit problems**.

**Losses decrease with increasing Micro DG penetration.** It is noted that circuit losses decrease dramatically compared to transformer losses.

In terms of CO<sub>2</sub> emissions, the reduction in network losses in combination with local power generation from Micro CHP and PV results in **significant reduction in CO<sub>2</sub> emissions** thanks to avoided emissions from the marginal plant of the system.

Overall, **network cost decreases** thank to losses reduction.

Finally, **Micro DG penetration decreases the maximum GSP power flows** with potential benefits coming from deferral of transmission system investments.

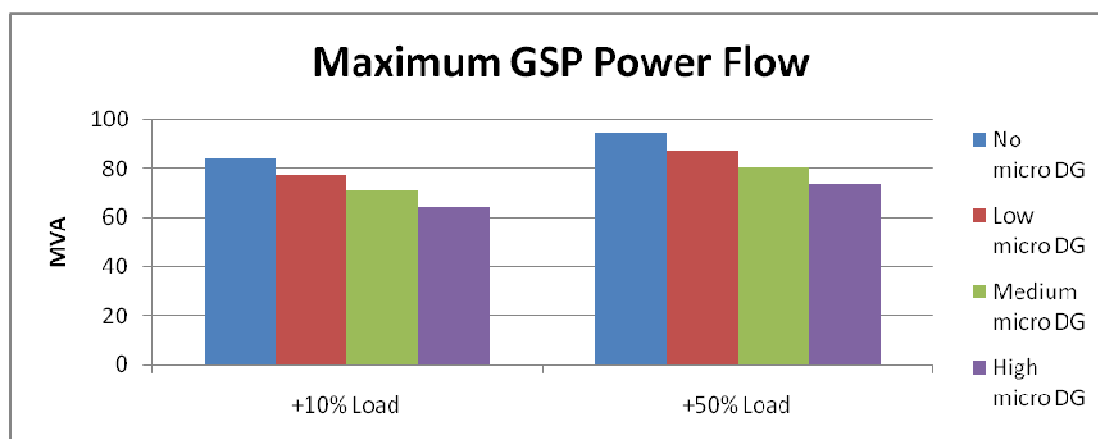


Figure 4.27. Maximum GSP power flow.

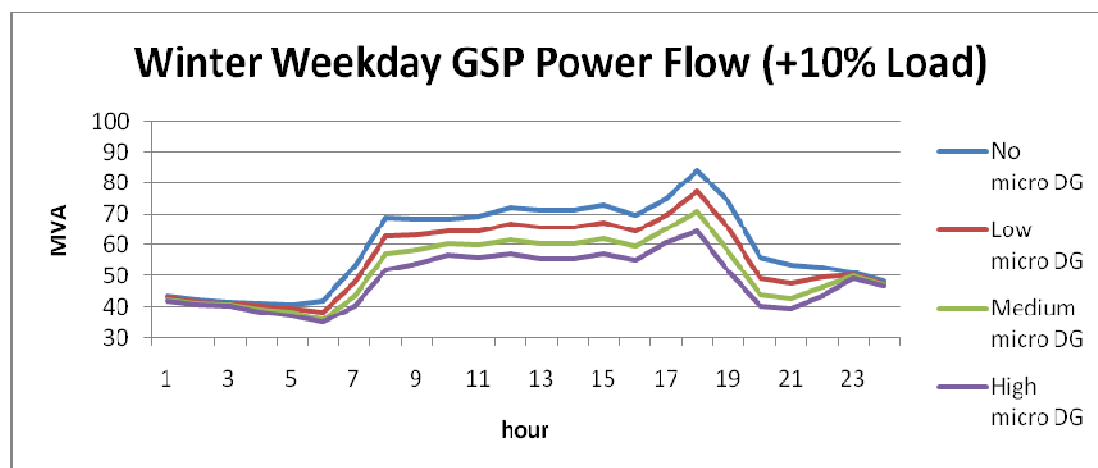


Figure 4.28. Winter weekday GSP power flow (+10% load).

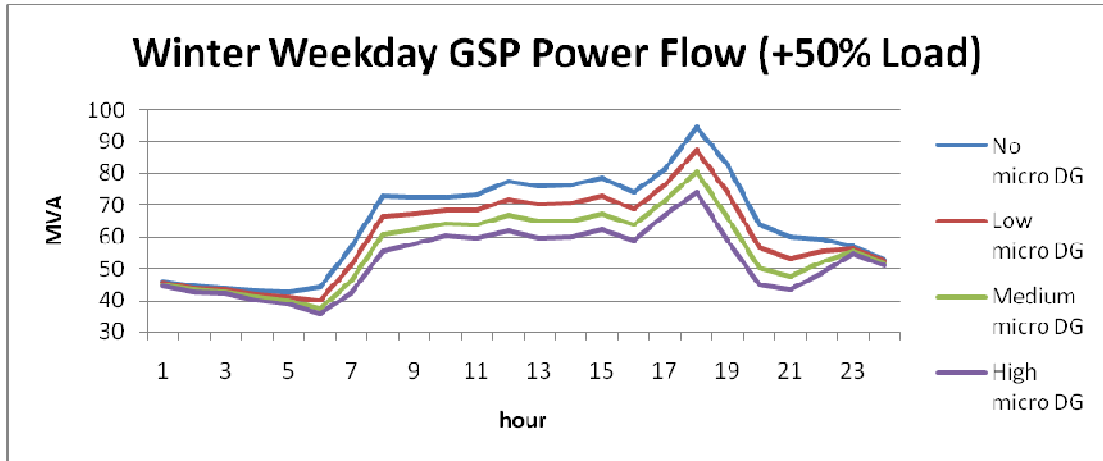


Figure 4.29. Winter weekday GSP power flow (+50% load).

## 5. Distribution Network Analysis for FYROM

### 5.1 MicroGrid Scenarios

#### 5.1.1 General Information

The distribution network we have worked with has four voltage levels (0.4kV, 10kV, 35kV and 110kV) and is characterized by high losses and a very weak low voltage network. Basic information regarding the structure of the network is given on Table 5.1. The composition of the load is given on Table 5.2 and its current peak value is 450MW.

Voltage level	0.4kV	10kV	35kV	110kV
<b>Number of different module types</b>	7	3	1	1
<b>Number of each module type per GSP</b>	Module type 1: 60	Module type 1: 2	1	1
	Module type 2: 48	Module type 2: 2		
	Module type 3: 49	Module type 3: 2		
	Module type 4: 46			
	Module type 5: 60			
	Module type 6: 48			
	Module type 7: 12			
<b>Total number of modules per GSP</b>	323	6	1	1
<b>Number of feeders per module type</b>	Module type 1: 3	Module type 1: 3	4	3
	Module type 2: 4	Module type 2: 5		
	Module type 3: 5	Module type 3: 15		
	Module type 4: 6			
	Module type 5: 7			
	Module type 6: 8			
	Module type 7: 10			
<b>Total number of feeders</b>	1817	16	4	3
<b>Total number of transformers</b>	323	6*2=12	1*2=2	1*2=2
<b>Capacity of transformers per module type (in MVA)</b>	Module type 1: 0.05	Module type 1: 4	40*2=80	300*2=600
	Module type 2: 0.1	Module type 2: 8		
	Module type 3: 0.16	Module type 3: 31.5		
	Module type 4: 0.25			
	Module type 5: 0.4			
	Module type 6: 0.63			
	Module type 7: 1			

Table 5.1. Structure of the FYROM distribution network

	0.4kV	10kV	35kV	110kV
Residential with electrical heating	3.76%	0%	0%	0%
Residential without electrical heating	46.57%	0%	0%	0%
Industrial	0%	10%	1%	1%
Commercial	6.67%	0%	0%	0%
<b>Total</b>	<b>57%</b>	<b>10%</b>	<b>1%</b>	<b>32%</b>

Table 5.2. Load composition of the FYROM distribution network.

Two scenarios for the load at LV (low load: +10% and high load: +50% with respect to the current load at LV) and three scenarios for micro DG penetration (Figure 5.1) were investigated.

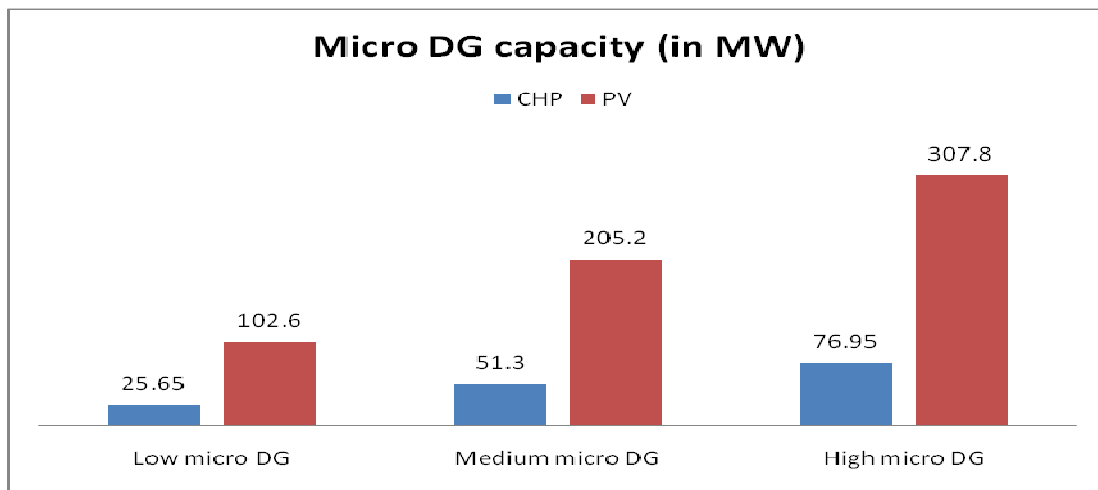


Figure 5.1. Micro DG capacity.

### 5.1.2 Benefits Related to Reinforcement Cost

The reduction in the annualized reinforcement cost by the installation of micro DG (with regard to the base case) for the low load scenario is depicted on Figure 5.2.

We can see that the reinforcement cost is reduced when micro DG capacity is increased because reinforcement is driven by the demand; the significant required reinforcement is related to violations of both voltage and thermal limits (almost equally significant) and mostly to the low voltage level. It is very interesting to observe that under passive management, a 50% penetration of micro DG (low micro DG case) cannot mitigate the required reinforcement due to the severity of the network problems (the reinforcement cost in the no and low micro DG cases is the same). On the other hand, the same micro DG penetration brings significant benefits under active management (due to the very low cost of implementing active management in comparison with the cost of replacing feeders suffering from voltage problems); the same trend is observed in the medium and high micro DG scenarios, where the reduction in reinforcement cost under active management is much higher than the respective one under passive management. This difference

becomes lower when we move from low to high micro DG penetration since the voltage problems arising become less severe. Since the voltage problems arising at the network are driven by the load (voltage drop problems), their severity decreases as the micro DG penetration increases; in accordance with our comments in the main deliverable, active management with tap changers constitutes the least reinforcement cost option in the low micro DG case (severe voltage drop problems) while active management without tap changers gives the lowest reinforcement cost in the medium and high micro DG cases (moderate voltage drop problems). As discussed in the main deliverable, the cost of deploying active management with tap changers is much less affected by the severity of the voltage problems at the network; this is why the reduction in reinforcement cost remains constant when we move from medium to high micro DG penetration under this strategy.

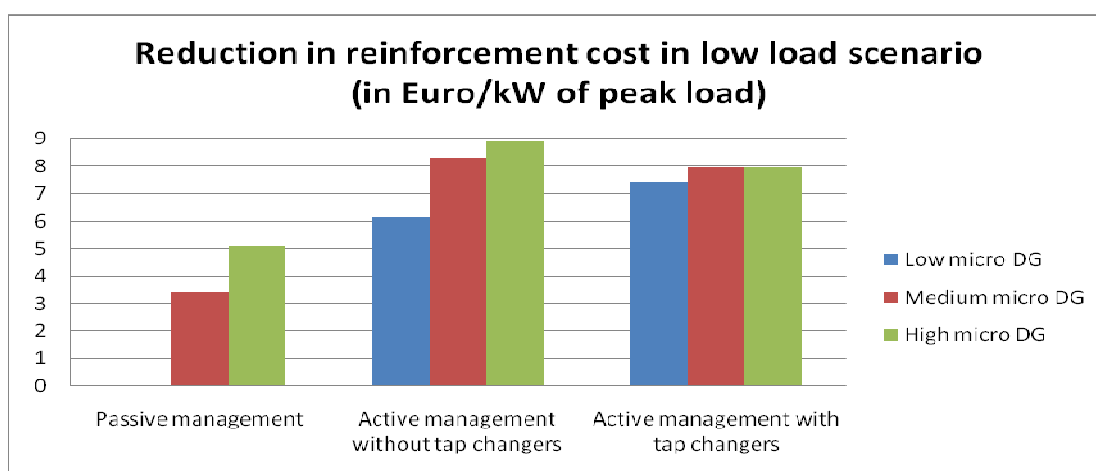


Figure 5.2. Reduction in reinforcement cost in low load scenario.

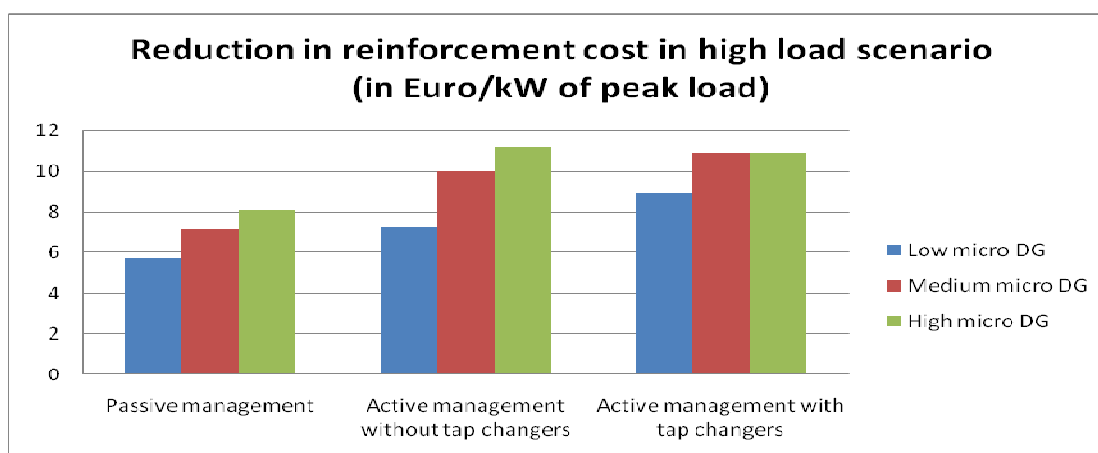


Figure 5.3. Reduction in reinforcement cost in high load scenario.

The respective reduction for the high load case is depicted on Figure 5.3; same trends with the low load case are observed. For low and high micro DG penetration, the

strategies giving the lowest reinforcement cost are the same as in the low load scenario (AM with tap changers and AM without tap changers respectively). Since the voltage drop problems are more severe now (due to the greater demand), AM with tap changers gives the lowest cost for a medium micro DG penetration (while AM without tap changers was the least reinforcement cost option for the same penetration in the low load case); the same reason leads to a more obvious difference between passive and active management than in the low load case.

### 5.1.3 Benefits Related to Losses

The losses reduction by the installation of DG for the low load scenario under each micro DG scenario and each operating strategy is presented at Figure 5.4. Under a specific strategy, when we increase micro DG penetration, the power flow from the GSP to the demand decreases (as more of the power required by the load is supplied by micro DG) and thus losses are reduced. Losses under passive management are lower in every micro DG scenario because in this case the voltage problems arising at the network are solved by replacing the suffering feeders with feeders of smaller resistance (while under active management existing feeders are not replaced) and (active) losses of the network depend highly on the resistance of its assets. This difference in losses between passive and active management becomes less significant as micro DG penetration is increased, since less voltage drop problems occur and thus less feeders are replaced under passive management.

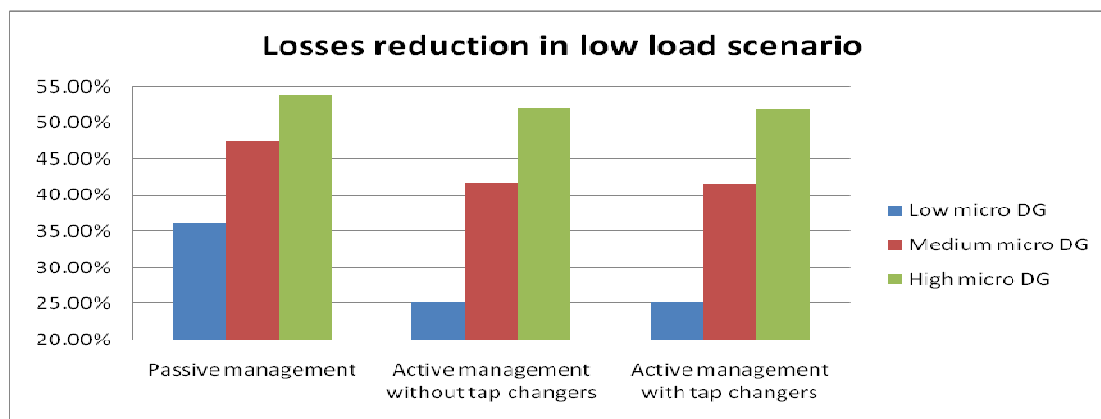


Figure 5.4. Losses reduction in low load scenario.

Reduction in the (annual) cost of losses (Figure 5.5) follows the same trends as the losses reduction since amount and cost of losses are proportional.

The respective results for the high load case are shown on Figure 5.6 and Figure 5.7. Similar trends to the low load case are observed. Since voltage drop problems are more severe now (due to the greater demand), the differences between the different operating strategies are more obvious.

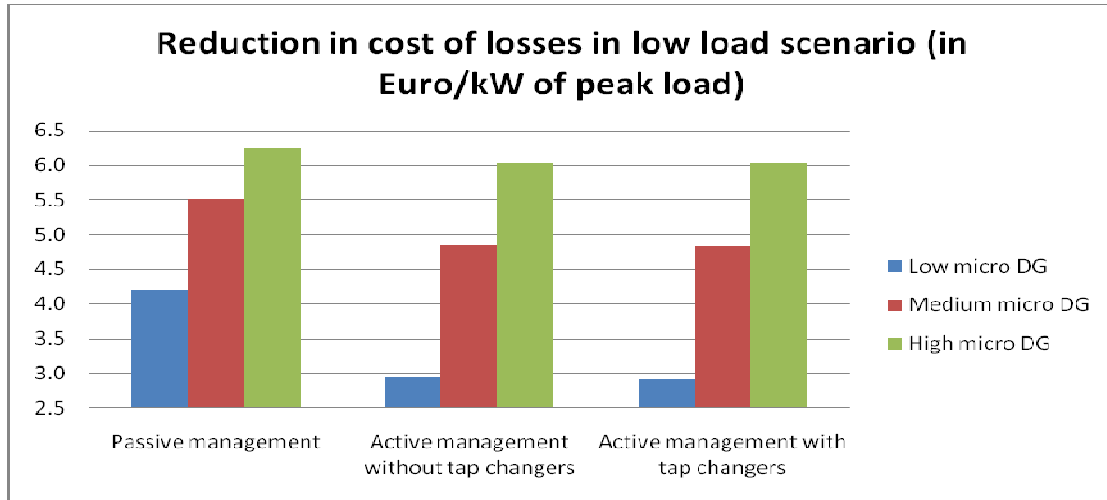


Figure 5.5. Reduction in cost of losses in low load scenario.

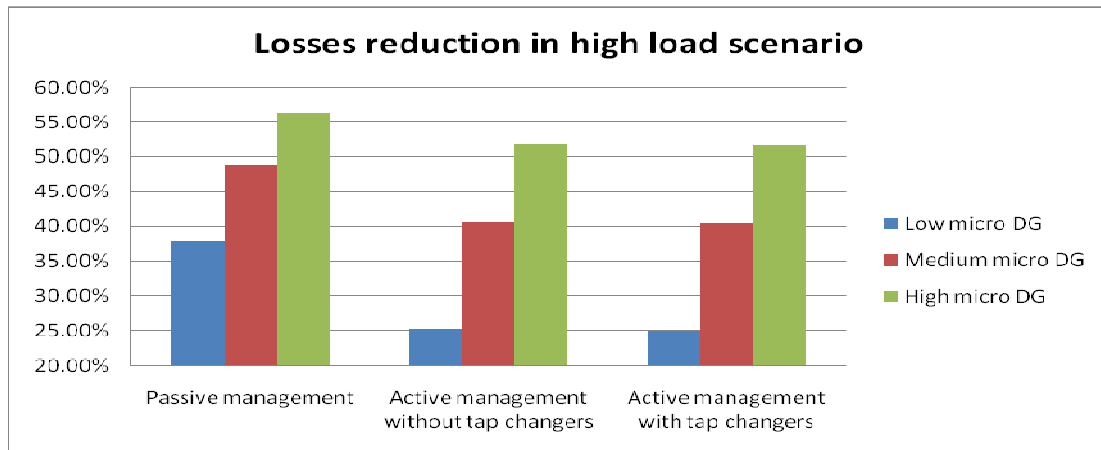


Figure 5.6. Losses reduction in high load scenario.

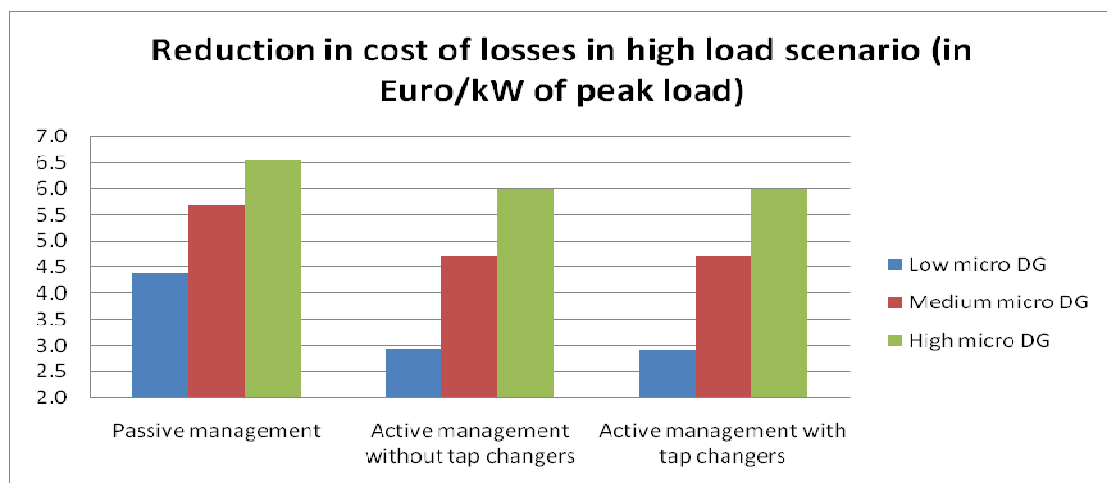


Figure 5.7. Reduction in cost of losses in high load scenario.

### 5.1.4 Benefits Related to Total Network Cost

The reduction in total network cost (sum of the reduction in the annualized reinforcement cost and the reduction in the annual cost of losses) in the low load scenario per kW of peak load is presented in Figure 5.8. We can observe that high micro DG penetration gives the lowest network cost under every strategy because both reinforcement cost and cost of losses are the lowest with this penetration. Moreover, active management gives the lowest network cost in each micro DG penetration scenario (with tap changers in the low micro DG scenario and without tap changers in the medium and high micro DG scenarios); this is due to the fact that even though the cost of losses is lower under passive management, the reinforcement cost is much lower under active management. The same reduction is shown on Figure 5.9 per kW of micro DG installed. Under passive management, the reduction in network cost is very low in the low micro DG scenario (because there is no reduction in the reinforcement cost, as discussed in section 5.1.2); thus, the incremental benefit of micro DG (value of the next kW of micro DG) increases when we move from low to medium micro DG. For medium micro DG the incremental benefit saturates, and when we move to high micro DG it is decreased. Under active management, this saturation effect has already taken place in the low micro DG penetration and the incremental benefit of micro DG decreases as we move from low to high micro DG.

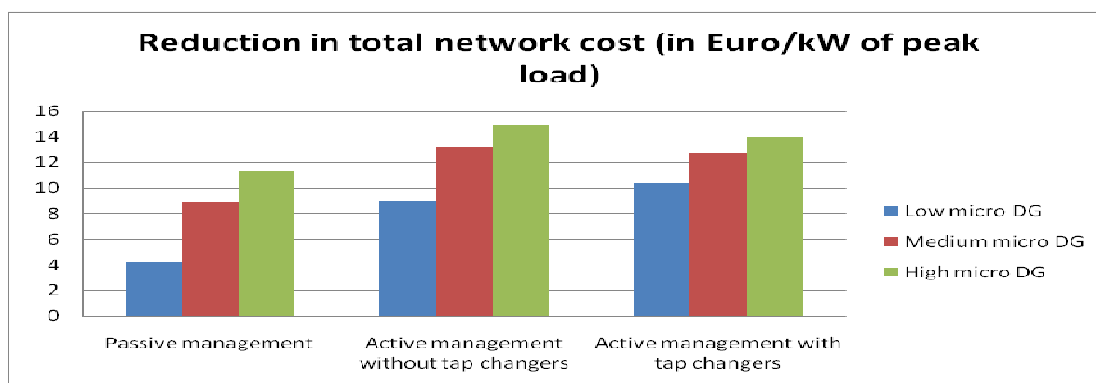


Figure 5.8. Reduction in total network cost (1).

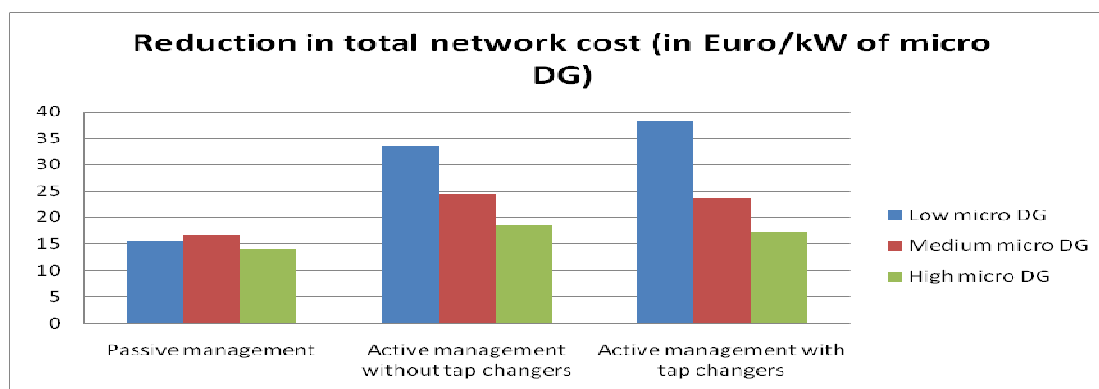


Figure 5.9. Reduction in total network cost (2).

The respective results for the high load case are depicted on Figure 5.10 and Figure 5.11; similar trends to the low load scenario are observed. For a specific micro DG penetration and a specific operating strategy, the incremental benefit of micro DG is much higher in the high load case (compare Figure 5.9 and Figure 5.11), since the voltage drop problems arising at the network are more severe and thus there is more room for the beneficial effects of extra micro DG capacity.

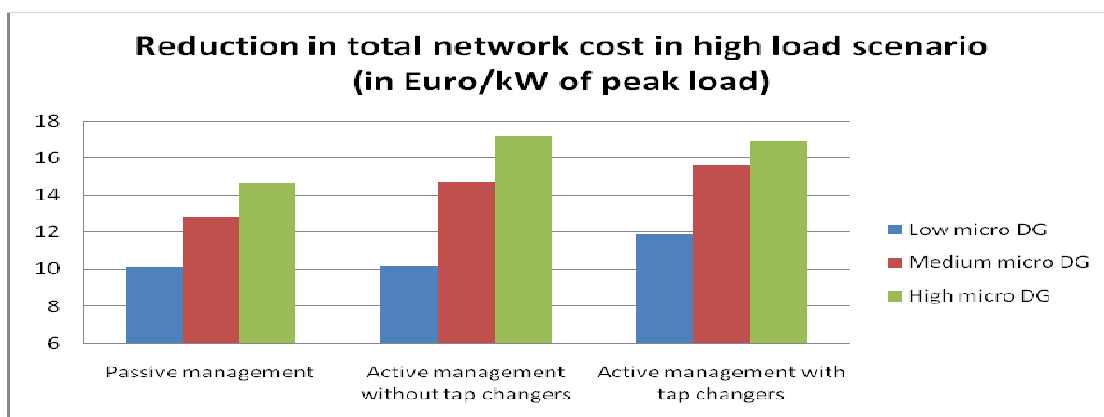


Figure 5.10. Reduction in total network cost in high load scenario (1).

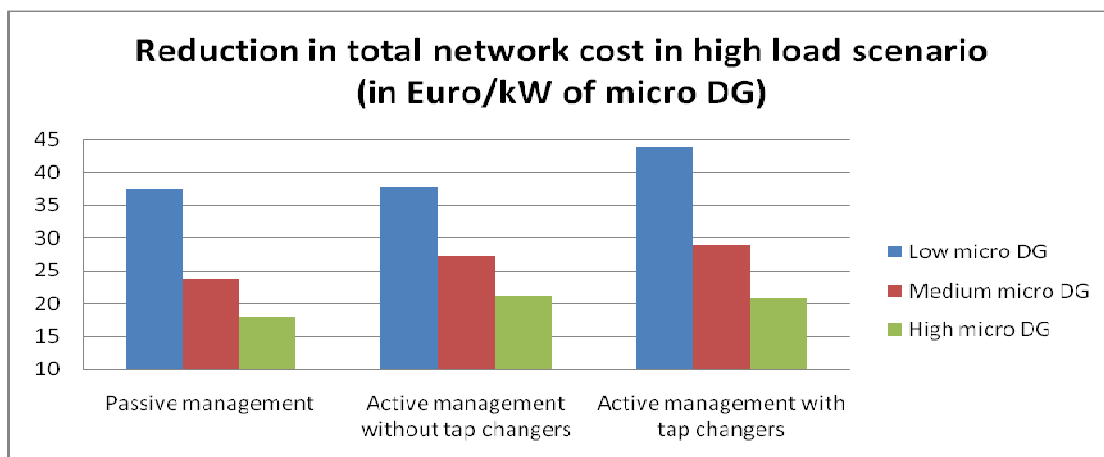


Figure 5.11. Reduction in total network cost in high load scenario (2).

### 5.1.5 Benefits Related to Local Power Generation

The annual energy production by each type of micro DG in each penetration scenario is found on Figure 5.12; the big difference in energy production between micro CHP and micro PV is due to their capacity share (20% of the total micro DG capacity is CHP capacity while 80% is PV capacity).

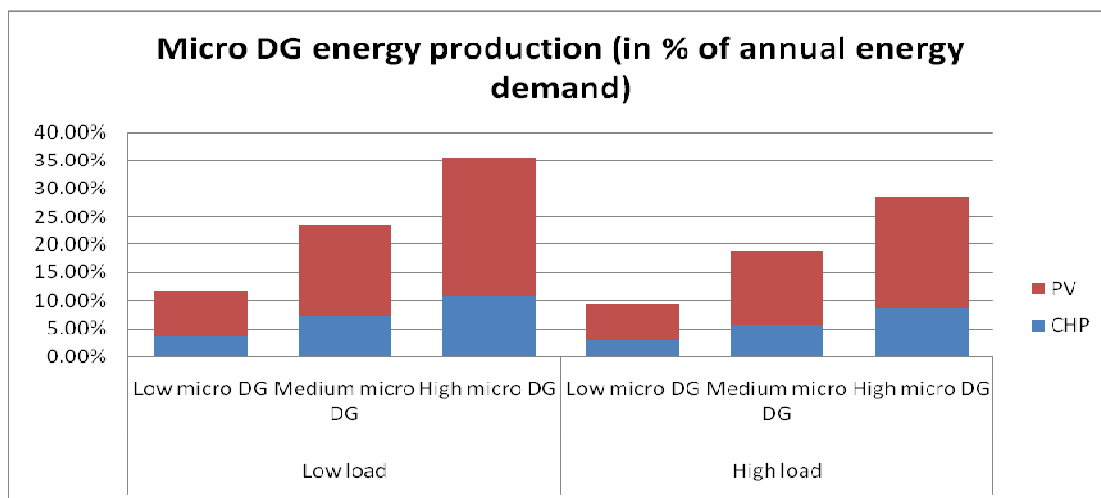


Figure 5.12. Micro DG energy production.

The maximum power flowing on the GSP (boundary between the examined distribution network and the upward transmission network) in the low load scenario (for simplicity reasons only for the optimal operating strategy -the strategy giving the lowest total network cost- in each micro DG scenario) is presented on Figure 5.13. This maximum power flow has a direction from the transmission system to the examined network (power import) in every micro DG scenario; as the micro DG penetration is increased, more of the power required by the load is supplied by local generation and thus the import from transmission is reduced. The observed reduction in the maximum power flow on the GSP is particularly relevant for transmission investment decisions. The same trend is observed in the high load case.

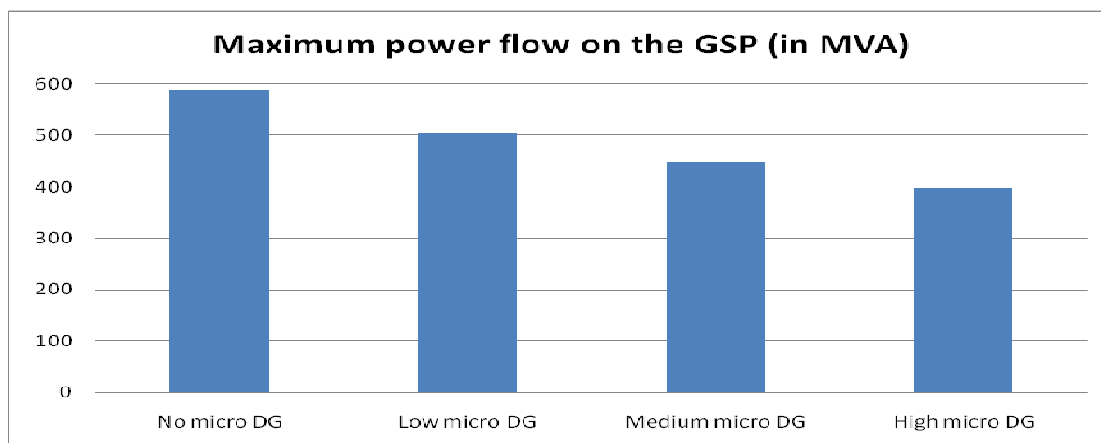


Figure 5.13. Maximum power flow on the GSP.

The hourly profile of the power flowing on the GSP (which expresses the demand curve of the examined distribution network) in a spring/autumn weekday (period of highest demand in the network) is depicted on Figure 5.14. The PV generation at 9.00-16.00 changes radically (PV constitute the largest part of micro DG in the network) the shape of

the profile curve at this time window, and the time that the morning peak occurs is altered (11.00 in the no DG case and 9.00 in each of the micro DG cases). Even though the CHP generators constitute a much smaller part of micro DG in the network, their peak generation at 18.00-22.00 (when heat demand presents its peak) changes slightly the shape of the profile curve at this time window and the time that the night peak occurs is altered when the CHP penetration becomes high (night peak occurs at 20.00 in the no, low and medium micro DG scenario and 23.00 in the high micro DG scenario). These results are particularly relevant for central generation scheduling. Same trends are observed in the high load case.

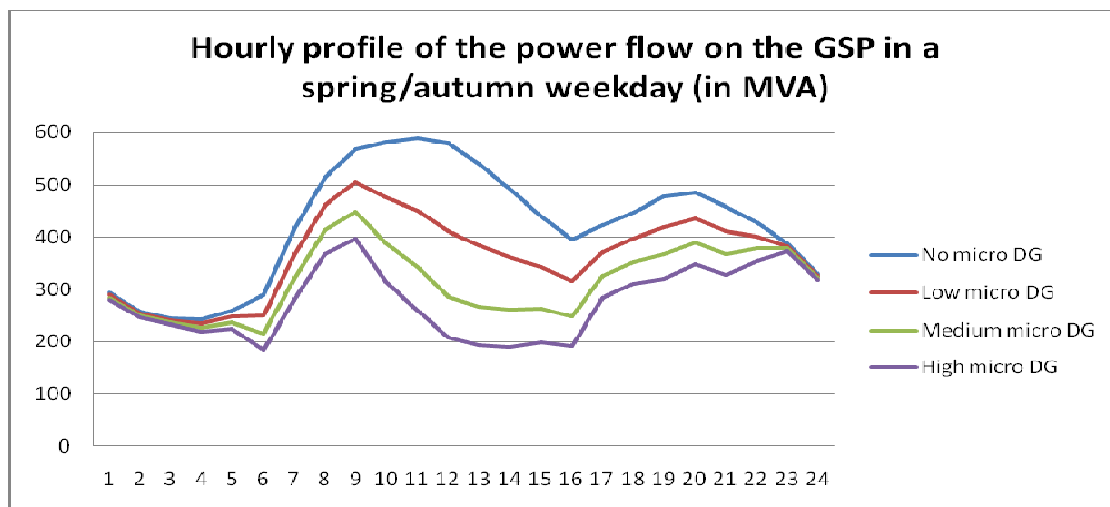


Figure 5.14. Hourly profile of the power flow on the GSP.

### 5.1.6 Environmental Benefits

As explained in detail in the main deliverable, the installation of micro DG results in  $CO_2$  emissions reduction because i) it reduces losses and ii) it displaces part of the central energy production (micro CHP generators also displace part of the heat production of conventional boilers); the marginal plant model (presented in the main deliverable) and a parametric analysis (for different values of the emission factor of the marginal plant) is used for the calculation of this reduction (for simplicity reasons only for the optimal operating strategy in each micro DG scenario).

The  $CO_2$  emissions reduction (with respect to the no DG case) caused by micro CHP energy production (Figure 5.15), by micro PV energy production (Figure 5.16), by the reduction of losses (Figure 5.17) and the total one (Figure 5.18) for the low load scenario are presented below. We observe that the emissions reduction caused by local power generation (both CHP and PV generation) and losses reduction increases linearly with the emission factor of the marginal plant, as described by the relevant equations in the main deliverable. For a certain emission factor of the marginal plant, the emissions reduction increases with the micro DG capacity (since larger capacity means larger local energy production and larger reduction in losses, as depicted on Figure 5.12 and Figure 5.4,

respectively). In every case, the greatest part of the total emissions reduction comes from micro PV energy production. Similar trends are observed in the high load case.

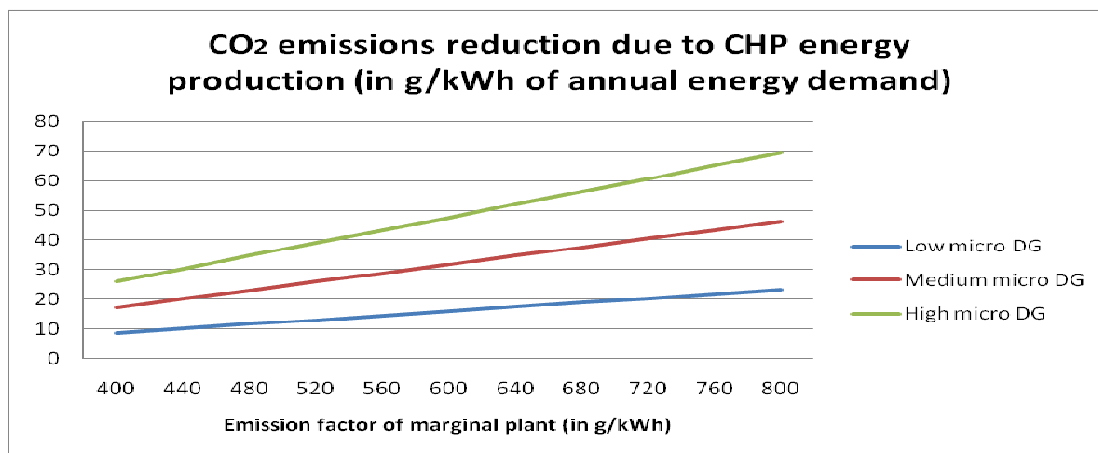


Figure 5.15. CO<sub>2</sub> emission reduction due to CHP energy production.

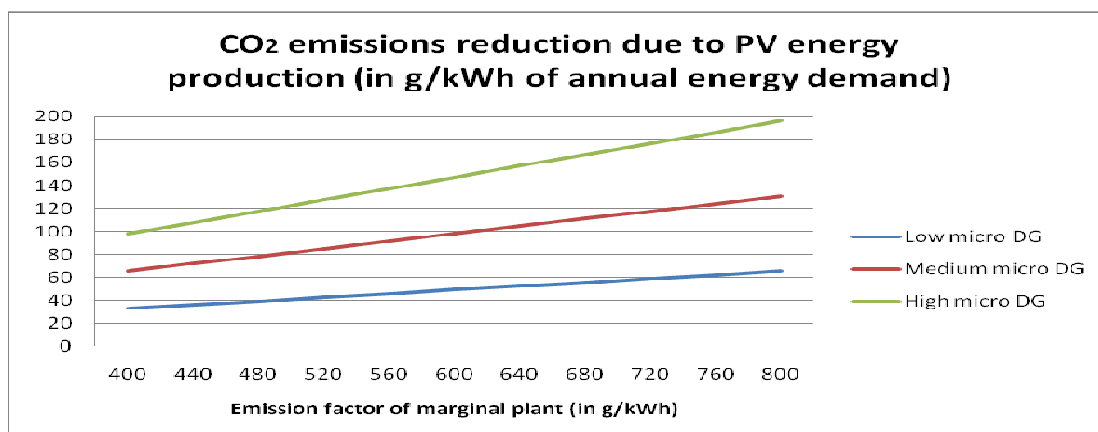


Figure 5.16. CO<sub>2</sub> emission reduction due to PV energy production.

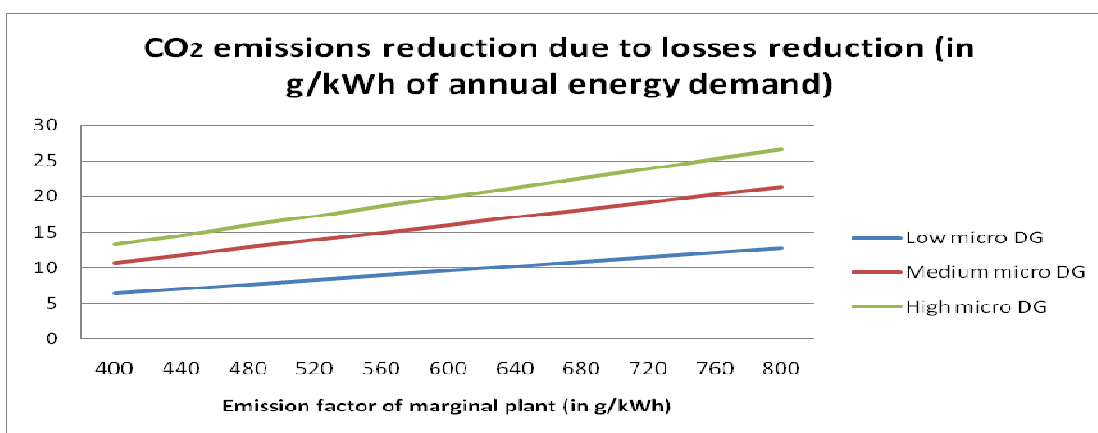


Figure 5.17. CO<sub>2</sub> emission reduction due to losses reduction.

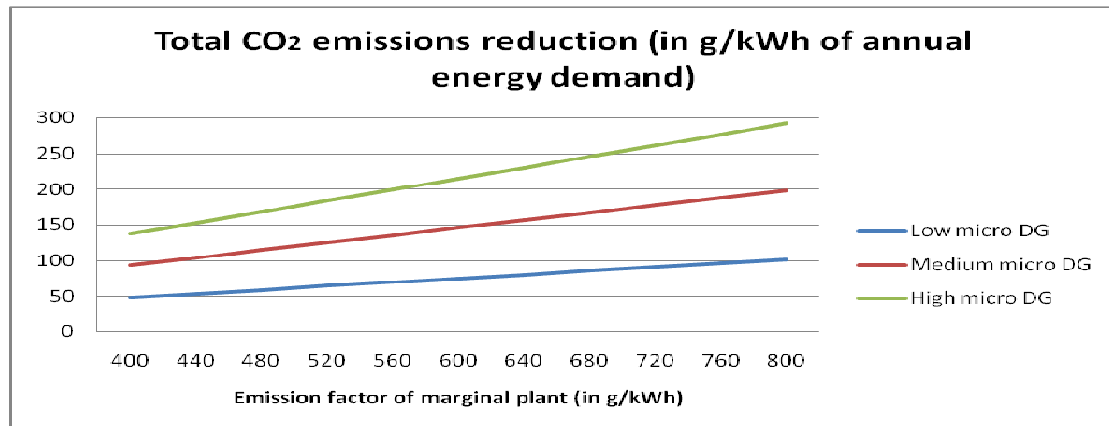


Figure 5.18. Total CO<sub>2</sub> emission reduction.

### 5.1.7 Conclusion

Our analysis on the FYROM distribution network shows that **very significant reinforcement** is required in both low and high load scenarios, related to **violations of both voltage and thermal limits** (almost equally significant) caused by demand, with the most severe problems arising at the **very weak low voltage level**. Since this reinforcement is driven by demand, the installation of **micro DG reduces reinforcement cost** (Figure 5.2 Figure 5.3) - by mitigating the above mentioned voltage drop and thermal problems- and as the micro DG penetration increases, the reinforcement cost is reduced. Evidence of the weakness of the network is the fact that a low micro DG penetration cannot extenuate at all the arising problems in the low load scenario under passive management. The deployment of **active management reduces further the reinforcement cost**, since the cost of implementing the active controls is much lower than the cost of replacing the feeders suffering from voltage problems. This benefit of active management becomes less apparent when the micro DG penetration increases and the demand decreases, as the emerging voltage drop problems become less severe. The active management strategy giving the lowest reinforcement cost depends on the relative severity of the emerging voltage problems and consequently on the demand and micro DG combination; active management with tap changers constitutes the least-reinforcement cost option in scenarios where the severity of the voltage problems is relatively high (low load-low micro DG, high load-low micro DG and high load-medium micro DG) and active management without tap changers constitutes the least-reinforcement cost option in scenarios where the severity of the voltage problems is relatively low (low load-medium micro DG, low load-high micro DG and high load-high micro DG).

The installation of **micro DG also reduces losses** at the network (and their cost) as part of the power required by the load is supplied locally and consequently the power flows from the GSP to the demand are reduced (Figure 13); thus, as the micro DG penetration increases, the losses reduction with respect to the base case (no DG) becomes more significant (Figure 5.4 and Figure 5.6). **Losses under passive management are lower** because the feeders suffering from voltage problems are replaced with feeders of smaller

resistance (which is not the case under active management); this difference becomes less apparent as micro DG penetration is increased and load is decreased, since the severity of the arising voltage problems is reduced.

Since micro DG reduces both the reinforcement cost and the cost of losses, it has a **beneficial impact** on the **total network cost**; as the micro DG penetration increases, the total network cost is reduced (Figure 5.8 and Figure 5.10) since this trend is observed in both reinforcement cost and cost of losses. **Active management reduces further the total network cost**, because its positive impact on the reinforcement cost is much more significant than its negative impact on the (cost of) losses. The active management strategy giving the lowest total network cost in each demand and micro DG combination is the strategy giving the lowest reinforcement cost for the same combination, since the differences in reinforcement cost between the two strategies (without and with tap changers) are much higher than the respective differences in cost of losses.

The **saturation effect on the incremental benefit of micro DG** (value of the next kW of micro DG) is observed in the low load scenario under passive management (Figure 5.9): it increases when we move from low to medium micro DG penetration (because the benefits from a low penetration are so limited that there is significant room for beneficial impacts from extra micro DG capacity) and it decreases when we move from medium to high micro DG penetration (because the benefits from a medium penetration are so significant that the room for beneficial impacts from extra micro DG capacity is limited). In the rest of the cases (Figure 5.9 and Figure 5.10), this saturation effect has already taken place in the low micro DG penetration and the incremental benefit of micro DG decreases as we move from low to high micro DG. Furthermore, for the same micro DG penetration and the same operating strategy, this incremental benefit is higher in the high load scenario, since the emerging voltage and thermal problems are more severe and thus there is more room for beneficial effects of extra micro DG.

The installation of **micro DG alters the aggregate demand curve of the FYROM distribution network** (Figure 5.14): micro PV generators (which constitute the largest part of micro DG) change radically the shape of the curve at morning and afternoon hours (as a result the time that the morning peak occurs in a spring/autumn weekday is altered) and micro CHP generators change slightly the shape of the curve at evening hours (as a result the time that the night peak occurs in a spring/autumn weekday is altered in the high micro DG case) due to the characteristics of their generation profile.

Finally, **micro DG reduces CO<sub>2</sub> emissions** since it reduces losses and it displaces part of the central electricity production (micro CHP generators also displace part of the heat production by conventional boilers). For a certain emission factor of the marginal plant of central generation, the emissions reduction with respect to the base case (no DG) increases with the micro DG penetration, as the losses reduction and the micro DG energy production become more significant (Figure 5.15 to Figure 5.18). The most significant component of emissions reduction comes from the displacement of central electricity production by micro PV energy production.

## 6. Distribution Network Analysis for the UK

### 6.1 MicroGrid Scenarios

#### 6.1.1 General Information

A UK distribution network with four voltage levels (0.4kV, 11kV, 33kV and 132 kV) and average characteristics with regard to the parameters of feeders and transformers was used in our analysis. The load is composed of 70% residential customers with electrical heating, 10% residential customers without electrical heating, 10% commercial customers and 10% industrial customers, and has a peak value of 265MW. Basic information regarding the structure of the network is given on Table 6.1.

Voltage level	0.4kV	11kV	33kV	132kV
<b>Number of different module types</b>	4	4	1	1
<b>Number of each module type per GSP</b>	250 for each module type	Module type 1: 4	4	1
		Module type 2: 4		
		Module type 3: 8		
		Module type 4: 8		
<b>Total number of modules per GSP</b>	1000	24	4	1
<b>Number of feeders per module type</b>	Module type 1: 2	Module type 1: 8	6	4
	Module type 2: 2	Module type 2: 8		
	Module type 3: 4	Module type 3: 8		
	Module type 4: 4	Module type 4: 8		
<b>Total number of feeders</b>	3000	192	24*2=48	4*2=8
<b>Total number of transformers</b>	1000	24*2=48	4*2=8	1*2=2
<b>Capacity of transformers per module type (in MVA)</b>	Module type 1: 0.1	Module type 1: 17.5*2	66*2	240*2
	Module type 2: 0.25	Module type 2: 7.5*2		
	Module type 3: 0.25	Module type 3: 17.5*2		
	Module type 4: 0.63	Module type 4: 7.5*2		

Table 6.1. Structure of the UK distribution network

Two scenarios for the load at LV (low load: +10% and high load: +50% with respect to the current load at LV) and three scenarios for micro DG penetration (Figure 6.1) were investigated.

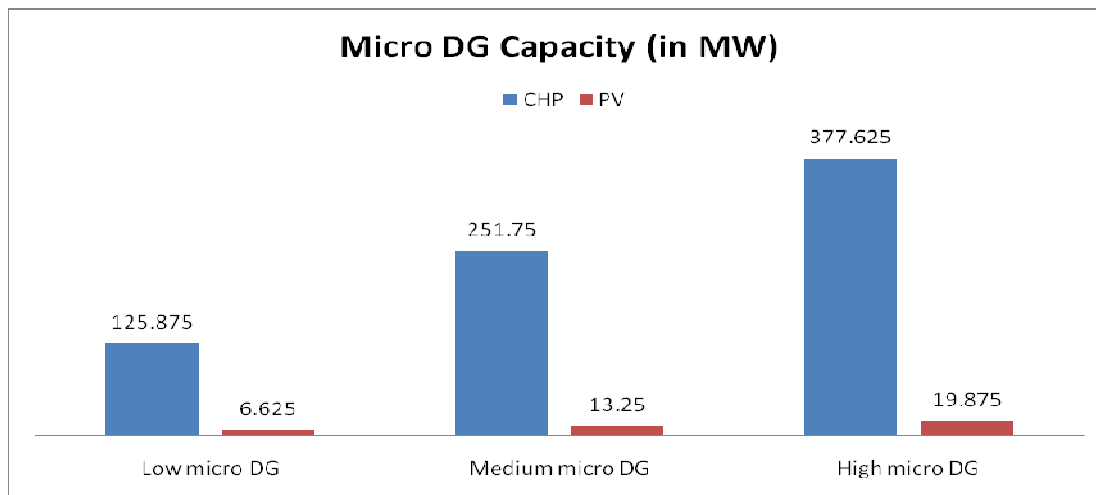


Figure 6.1. Micro DG capacity.

### 6.1.2 Benefits Related to Reinforcement Cost

The reduction in the annualized reinforcement cost by the installation of micro DG (with regard to the base case) for the low and the high load scenario is presented in Figure 6.2 to Figure 6.4 and Figure 6.5 to Figure 6.7 respectively.

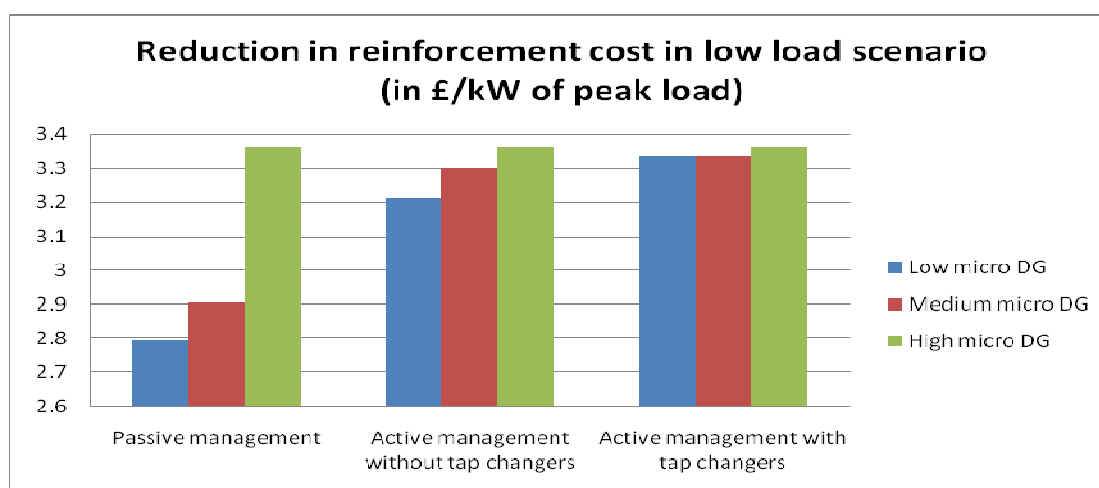


Figure 6.2. Reduction in reinforcement cost in low load scenario.

Figure 6.2 shows that as the installed micro DG increases in the low load case, the reinforcement cost decreases, which indicates that reinforcement in the network is driven by load. In the high micro DG scenario, no reinforcement is needed (no voltage, thermal

or fault level problems arise) and consequently the deployment of different strategies does not alter the reduction in reinforcement cost. In the low and medium micro DG scenarios, there are four feeders with voltage problems in the network and the reduction in reinforcement cost under active management is much higher than the respective one under passive management due to the very low cost of implementing active management in comparison with the cost of replacing these four feeders; this difference becomes lower when we move from low to medium micro DG penetration since these voltage problems become less severe. The strategy giving the lowest reinforcement cost in these two scenarios is active management with tap changers (which implies that the voltage problems are severe). Since these voltage problems are caused by load (voltage drop problem), their severity decreases when we move from low to medium micro DG penetration; the cost of deploying active management without tap changers decreases when the severity of the voltage problem decreases (13.35MVAR of reactive compensation are needed in the low micro DG scenario while only 4.96MVAR are needed in the medium micro DG scenario), while the cost of active management with tap changers remains constant (in both scenarios there is no reactive compensation needed and the only parameter changing is the position of the tap changer).

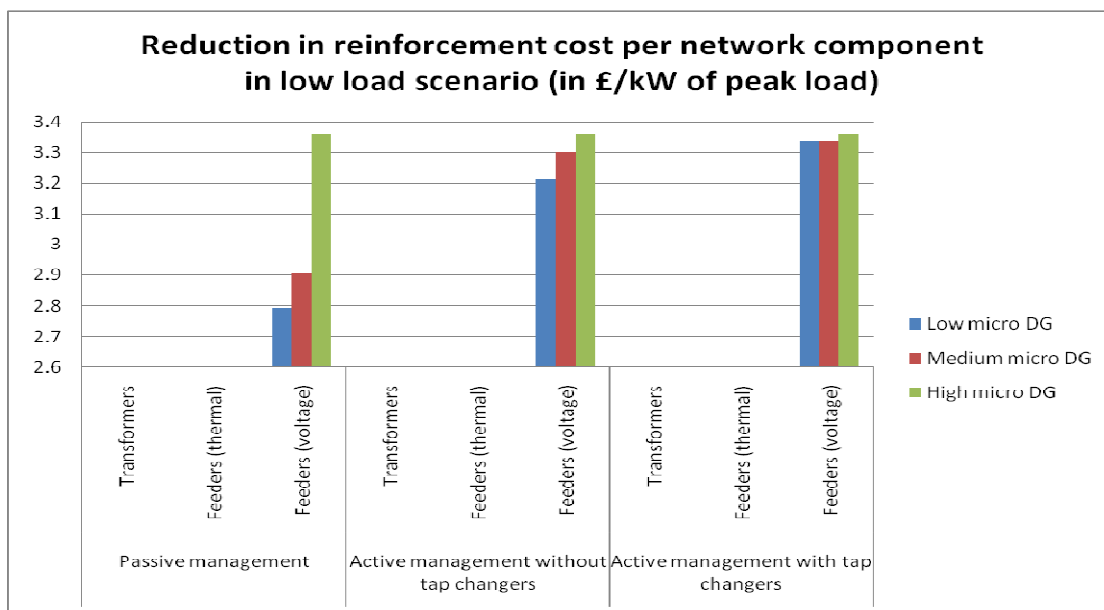


Figure 6.3. Reduction in reinforcement cost per network component in low load scenario.

As depicted in Figure 6.3, all the problems arising in the low load scenario are related to violations of voltage limits, which occur in 11kV and 33kV voltage levels, according to Figure 6.4. The problems arising at the 11kV network in the no DG case are solved by the installation of micro DG, irrespectively of its capacity and the strategy followed, while these factors affect the reinforcement cost at 33kV, as shown on Figure 6.4.

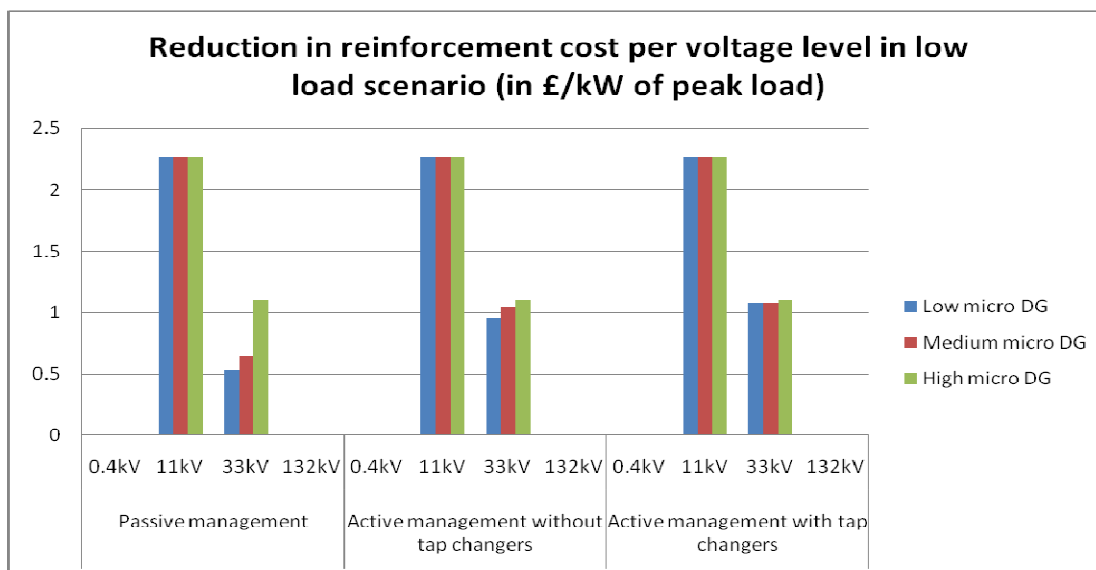


Figure 6.4. Reduction in reinforcement cost per voltage level in low load scenario.

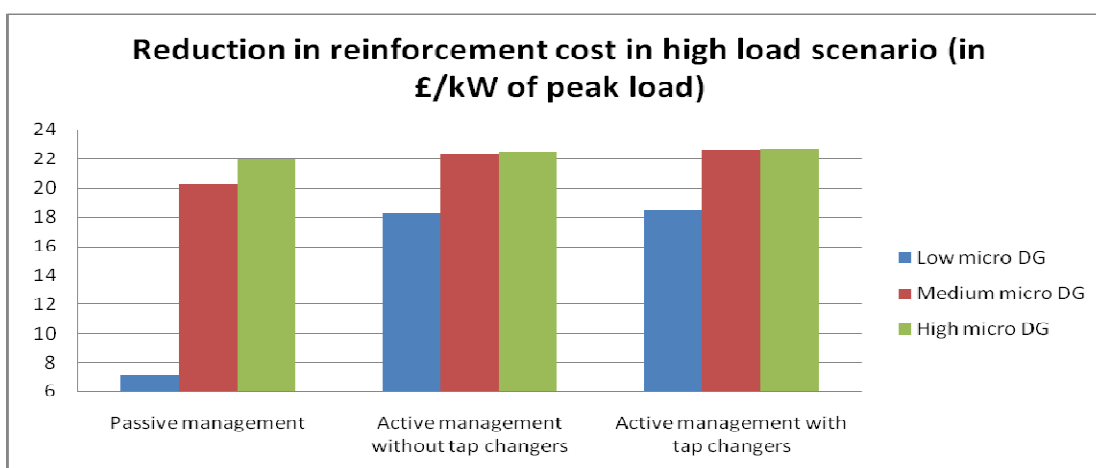


Figure 6.5. Reduction in reinforcement cost in high load scenario.

As in the low load case, in the high load case (Figure 6.5) the reinforcement cost decreases when micro DG increases under every operating strategy, and the strategy giving the lowest reinforcement cost under every micro DG penetration is again active management with tap changers. Since voltage drop problems are more severe now (due to the greater demand), the differences between the passive and active management are more obvious than in the low load case.

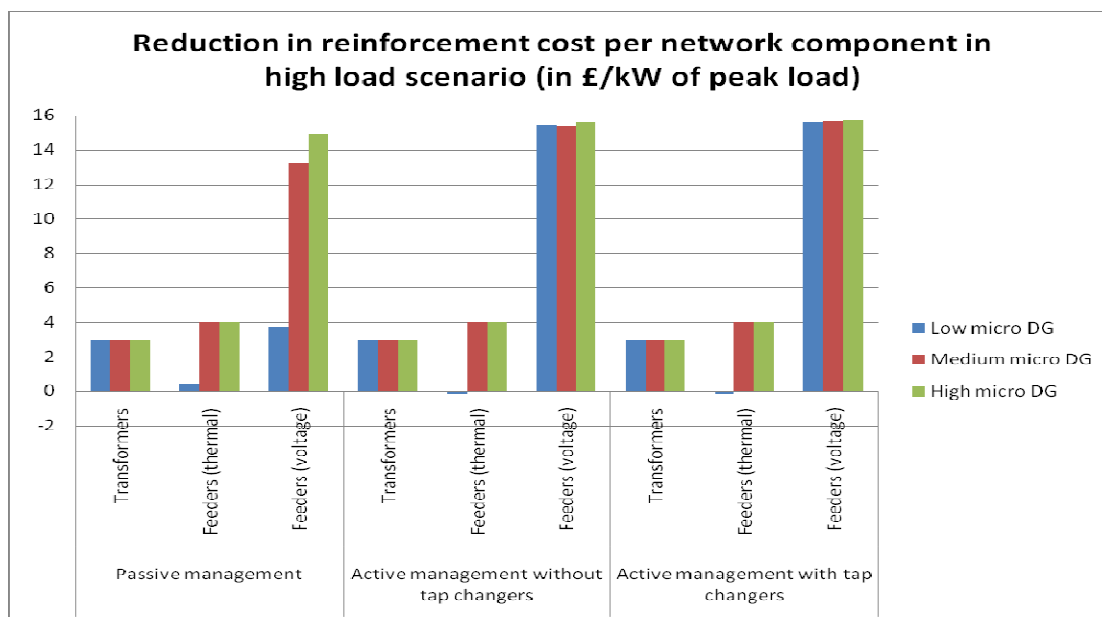


Figure 6.6. Reduction in reinforcement cost per network component in high load scenario.

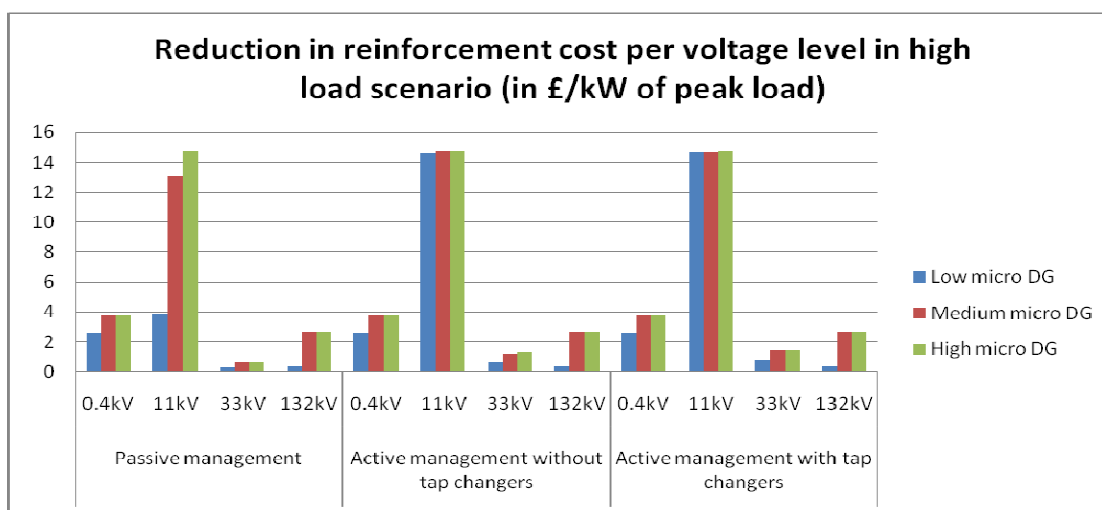


Figure 6.7. Reduction in reinforcement cost per voltage level in high load scenario.

As depicted on Figure 6.6 and Figure 6.7, the main component of reinforcement cost reduction with regard to the no DG case is related to feeders’ voltage problems and the 11kV voltage level (voltage problems at 11kV constitute the majority of network constraints arising in the no DG case). As expected, the reinforcement cost related to thermal problems is the same under the different operating strategies apart from the reinforcement cost of feeders with thermal problems in the low micro DG case, where we see (Figure 6.6) that the cost increases with respect to the no DG case under the two active management strategies. This is due to the fact that there are some feeders in the no DG and low DG cases that face both thermal and voltage problems: in the no DG case

(where passive management is deployed), voltage problems drive the reinforcement at these feeders (they require larger conductor size than the thermal problems) and thus thermal-related reinforcement cost is zero; deployment of active management solves voltage problems at these feeders (without the need of conductor replacement) but it cannot deal with the thermal problems and thus the latter drive conductor replacement and thermal-related reinforcement cost is not zero.

### 6.1.3 Benefits Related to Losses

The losses reduction by the installation of micro DG for the low load scenario under each micro DG scenario and each operating strategy is presented at Figure 6.8. When we move from low to medium micro DG penetration, the power flow from the GSP to the demand decreases (as more of the power required by the load is supplied by micro DG) and thus losses are reduced; on the other hand, when we move from medium to high micro DG penetration, the power flows are reversed (since DG capacity is higher than the load) and these reverse flows are so high that the losses are increased. Furthermore, we can see that under passive management losses are lower in low and medium micro DG scenarios; this is due to the fact that in the passive management case voltage problems are solved by replacing the suffering feeders with feeders of smaller resistance (while under active management existing feeders are not replaced) and (active) losses of the network depend highly on the resistance of its assets. This difference becomes less apparent as micro DG penetration is increased, since the severity of the arising voltage problems is reduced; in the high micro DG scenario no reinforcement is needed and consequently the deployment of different strategies does not alter the network and thus the losses reduction.

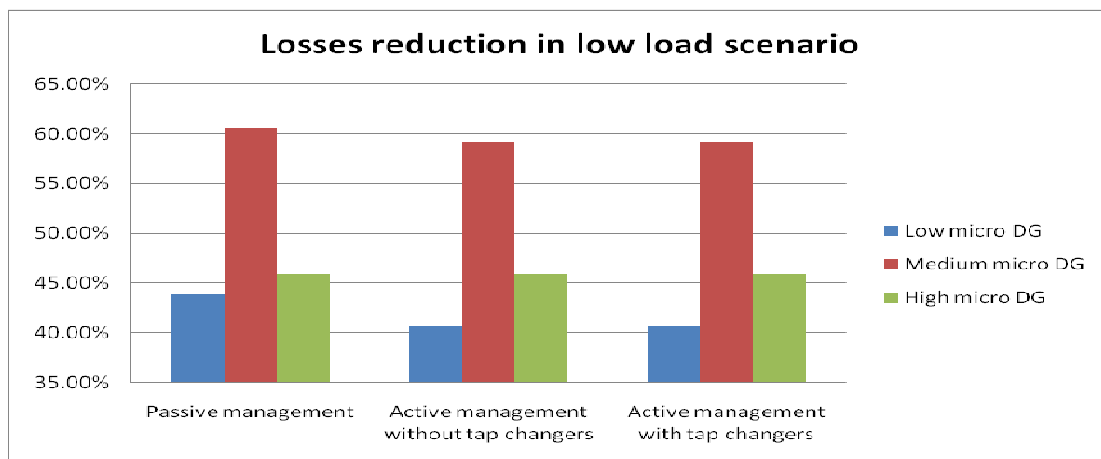


Figure 6.8. Losses reduction in low load scenario.

The breakdown of this losses reduction per network component and voltage level is presented at Figure 6.9 and Figure 6.10 respectively. The greatest reduction occurs at feeders and the 132kV voltage level. Since the difference between passive and active management is related to the way of resolving feeders' voltage problems, their difference in terms of transformers' losses is almost zero, as depicted on Figure 6.9. In the low and

medium micro DG scenarios, reinforcement is only needed in 33kV feeders facing voltage problems and this is the reason why the losses’ difference between passive and active management is mainly concentrated on the 33kV column on Figure 6.10 respectively.

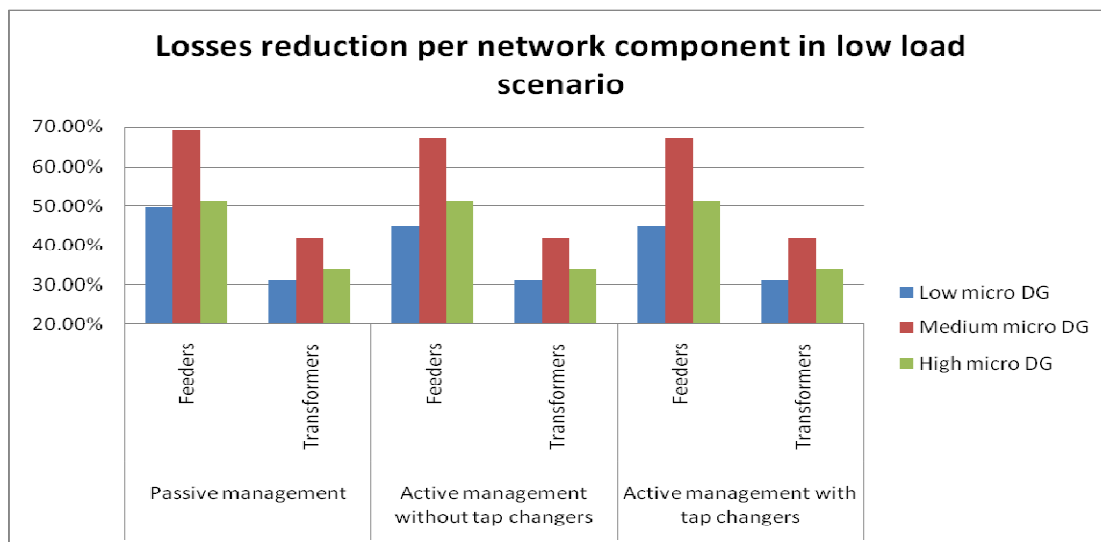


Figure 6.9. Losses reduction per network component in low load scenario.

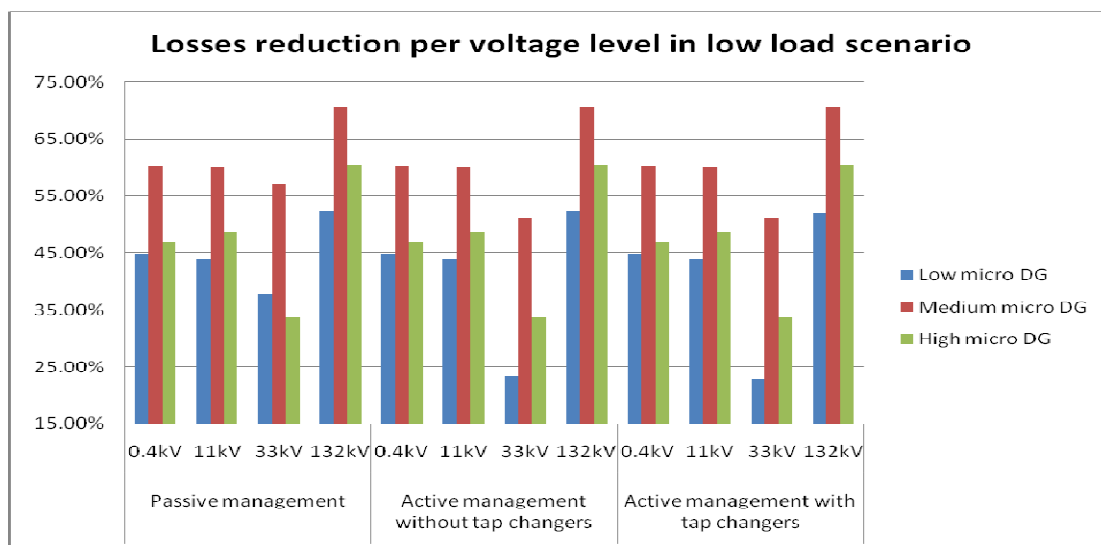


Figure 6.10. Losses reduction per voltage level in low load scenario.

Reduction in the (annual) cost of losses (Figure 11) follows the same trends as the losses reduction since amount and cost of losses are proportional.

Figure 6.12 to Figure 6.15 present the same results in the high load case. In contrast with the low load case, when we move from medium to high micro DG penetration, power flows from the GSP decrease and very large reverse power flows do not occur (DG capacity is lower than the load), and thus losses are reduced (Figure 6.12). Since the

voltage drop problems are more severe now, the difference in losses between passive and active management is more significant. The greatest losses reduction occurs at feeders (Figure 6.13) and at the 0.4 and 11kV voltage levels (Figure 6.14). The reduction in cost of losses (Figure 6.15) follows the same trends as losses reduction.

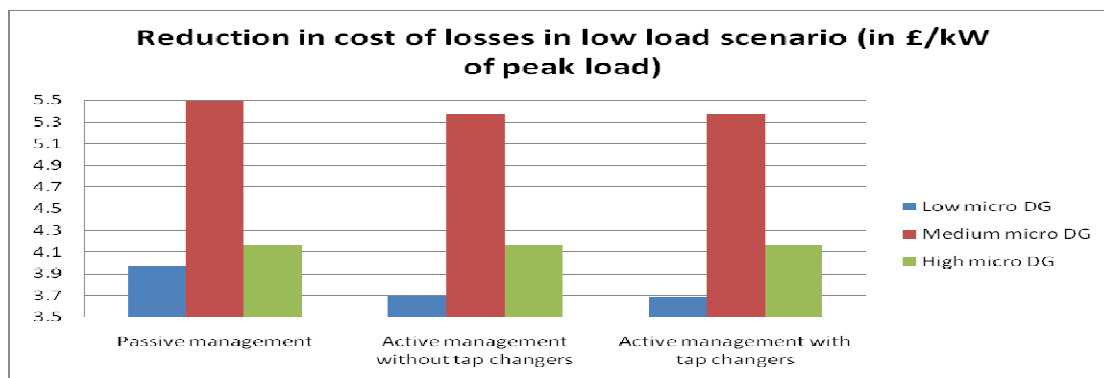


Figure 6.11. Reduction in cost of losses in low load scenario.

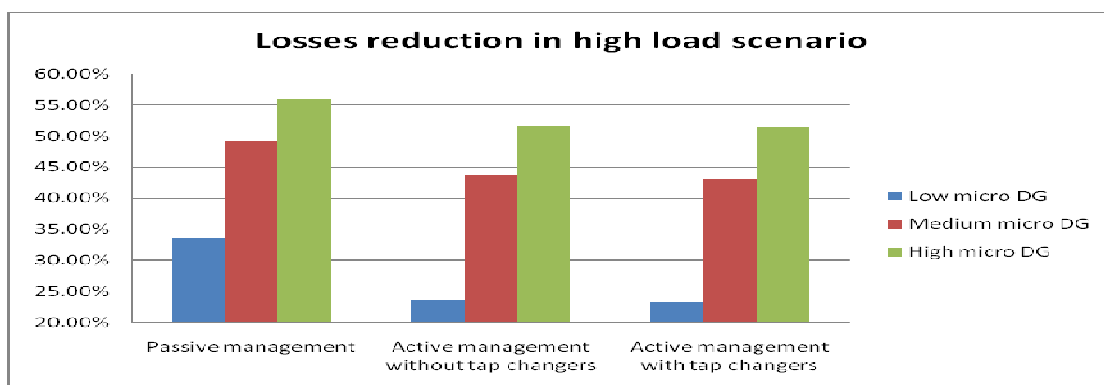


Figure 6.12. Losses reduction in high load scenario.

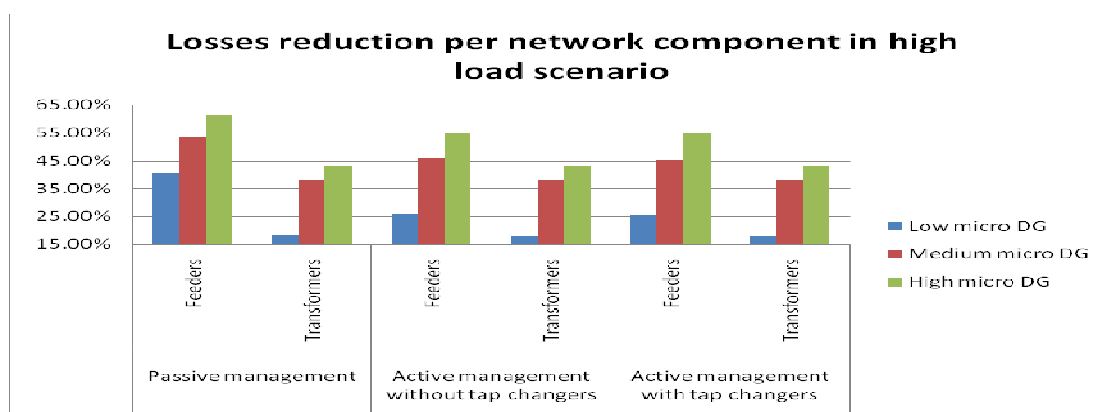


Figure 6.13. Losses reduction per network component in high load scenario.

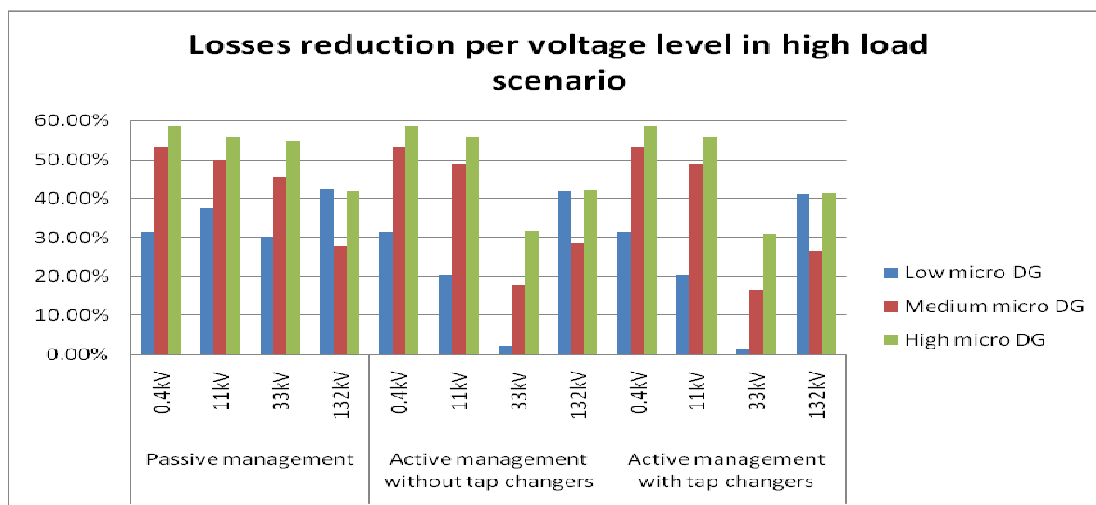


Figure 6.14. Losses reduction per network component in high load scenario.

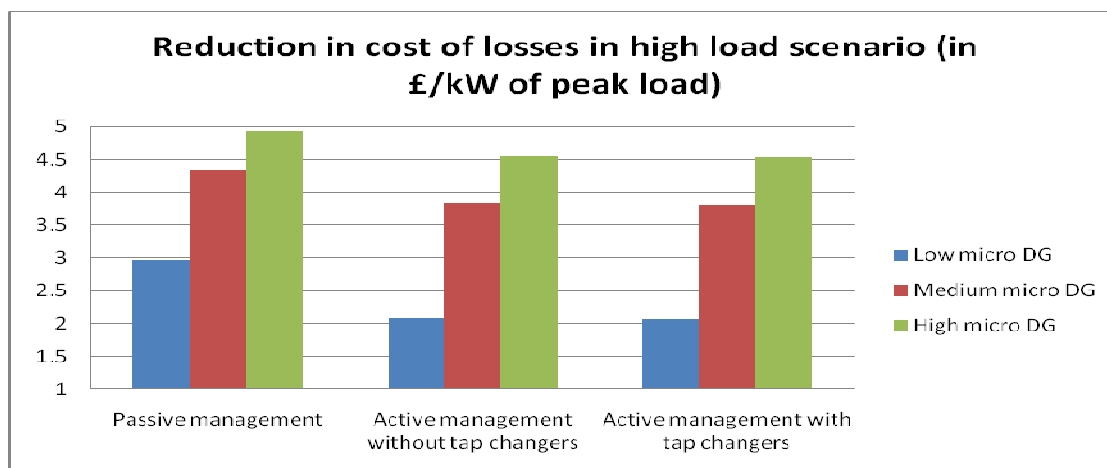


Figure 6.15. Reduction in cost of losses in high load scenario.

### 6.1.4 Benefits Related to Total Network Cost

The reduction in total network cost (sum of the reduction in the annualized reinforcement cost and the reduction in the annual cost of losses) in the low load scenario per kW of peak load is presented on Figure 6.16. We can observe that medium micro DG capacity gives the lowest network cost under every strategy (even though the reinforcement cost is lower in the high micro DG case, the cost of losses is much lower in the medium micro DG case) and active management with tap changers gives the lowest network cost in each micro DG penetration scenario (even though the cost of losses is lower under passive management, the reinforcement cost is much lower under active management with tap changers). The same reduction is shown on Figure 6.17 per kW of micro DG installed: we can see that the incremental benefit of micro DG (value of the next kW of micro DG)

decreases as its penetration increases, since the increase in installed micro DG reduces the available room for the beneficial effects of extra micro DG capacity.

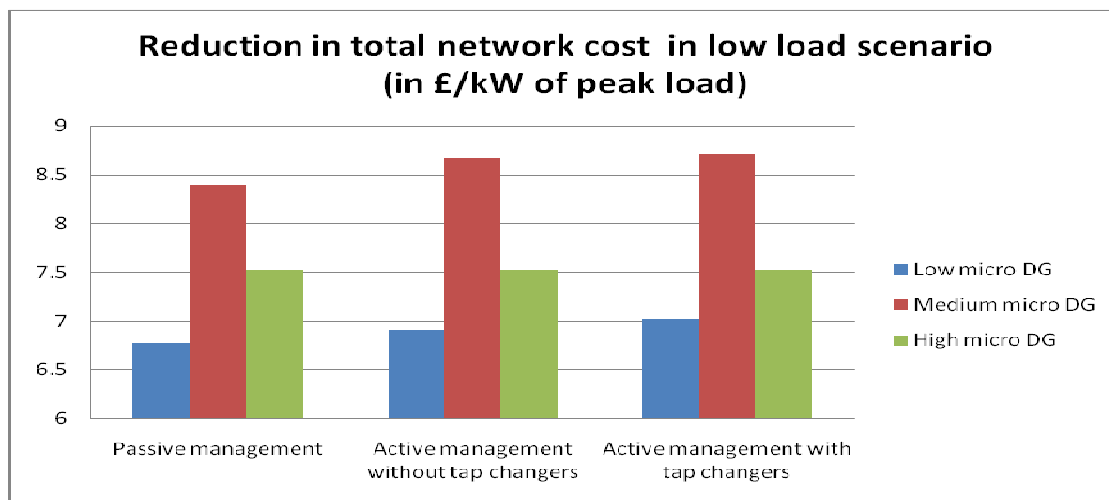


Figure 6.16. Reduction in total network cost in low load scenario (1).

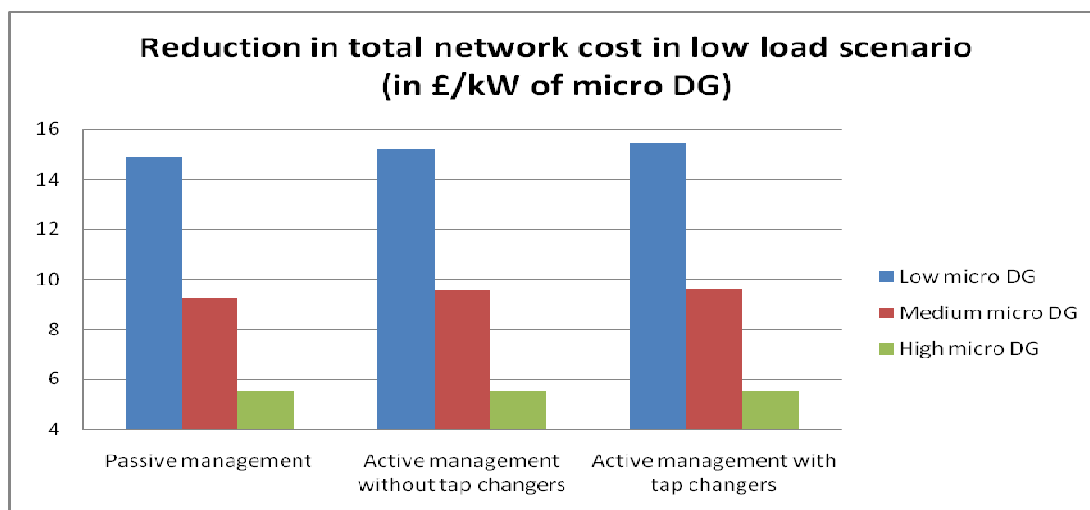


Figure 6.17. Reduction in total network cost in low load scenario (2).

The respective results for the high load scenario are depicted on the two following Figures. We can see (Figure 6.18) that high micro DG capacity gives the lowest network cost under every strategy (both reinforcement cost and cost of losses are the lowest with this capacity) and active management with tap changers gives the lowest network cost in each micro DG penetration scenario (even though the cost of losses is lower under passive management, the reinforcement cost is much lower under active management with tap changers). The reduction in network cost in the low micro DG scenario under passive management is very low as shown in Figure 6.18; thus the incremental benefit of micro DG increases when we move from low to medium micro DG as depicted on Figure 6.19. For medium micro DG the incremental benefit saturates, and when we move to high

micro DG it is decreased. For a specific micro DG penetration and a specific operating strategy, the incremental benefit of micro DG is much higher in the high load case (compare Figure 6.17 and Figure 6.19), since the voltage drop problems arising at the network are more severe and thus there is more room for the beneficial effects of extra micro DG capacity.

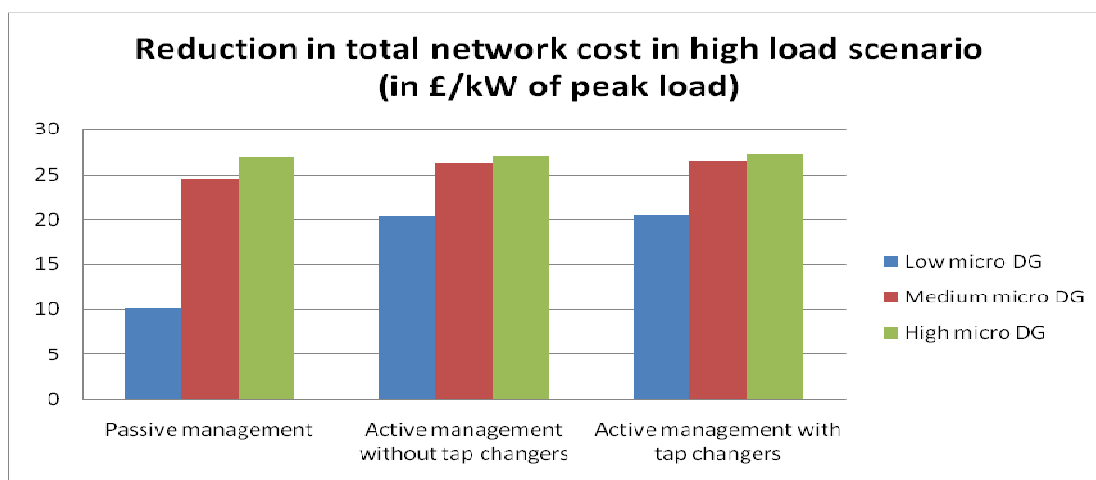


Figure 6.18. Reduction in total network cost in high load scenario (1).

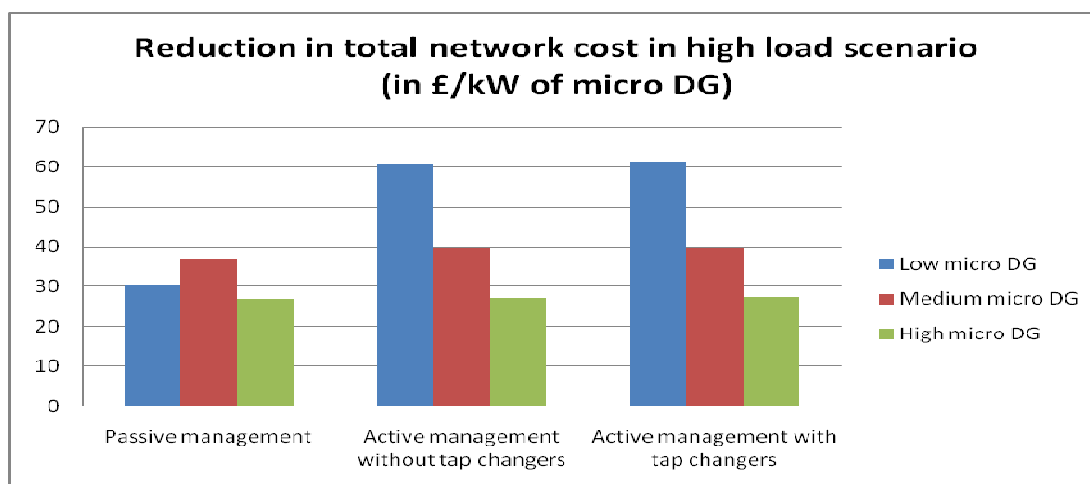


Figure 6.19. Reduction in total network cost in high load scenario (2).

### 6.1.5 Benefits Related to Local Power Generation

The annual energy production by each type of micro DG in each penetration scenario is found on Figure 6.20; the huge difference in energy production between micro CHP and micro PV is due to: i) their capacity share (95% of the total micro DG capacity is CHP capacity while only 5% is PV capacity and ii) their profiles (the average load factor is

much higher for CHP units). In the low load-high micro DG case, the annual DG energy production is higher than the annual energy demand.

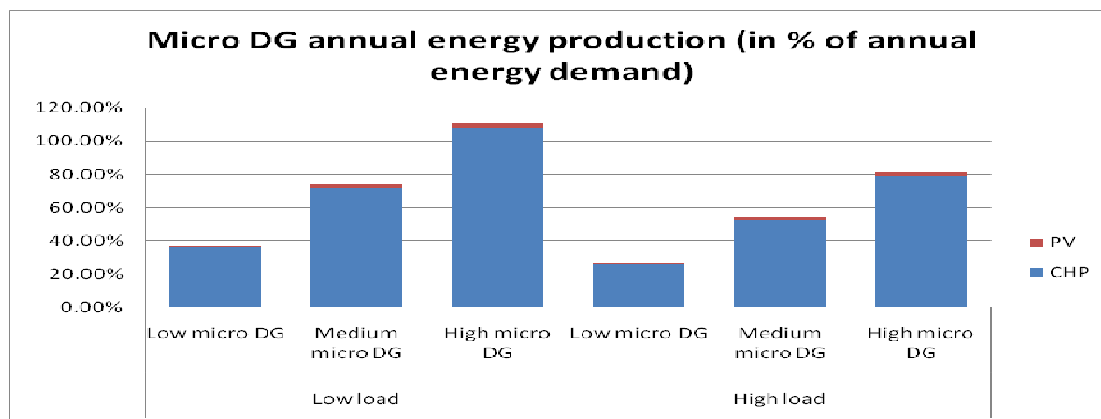


Figure 6.20. Micro DG annual energy production.

The maximum power flowing on the GSP (boundary between the examined distribution network and the upward transmission network) in the low load scenario (for simplicity reasons only for the optimal operating strategy, which is active management with tap changers in every micro DG scenario according to the results of section 6.1.4) is presented on Figure 6.21. The observed reduction by the installation of micro DG is particularly relevant for transmission investment decisions. The maximum power flow in the no, low and medium micro DG scenarios refers to power import from the transmission system; when we move from no to medium micro DG, more of the power required by the load is supplied by local generation and thus the import from transmission is reduced. On the other hand, the maximum power flow in the high load scenario refers to power export to the transmission system; when we move from medium to high micro DG, local generation becomes higher than the load, and reverse power flows on the GSP emerge (and we can observe that the maximum reverse power flow in this scenario is higher than the maximum power flow in the low and medium micro DG scenarios).

The hourly profile of the power flowing on the GSP (which expresses the demand curve of the examined distribution network) in a winter weekday (period of highest demand in the network) is depicted on Figure 6.22 (negative values correspond to power export to the grid). The profile curve is altered by the installation of micro DG (especially of micro CHP generators, which constitute its largest part): i) the whole curve moves downwards when micro DG is increased and power export occurs in the medium and high micro DG scenarios, ii) the peak occurs at 18.00 in the no micro DG case and at 17.00 in the rest of the cases and iii) two sudden dips are created at the time windows 6.00-9.00 and 18.00-22.00 (the last two changes are due to the fact that the heat demand and thus the profiles of the CHP generators present their peaks at these time windows). These results are particularly relevant for central generation scheduling.

The same results for the high load case are presented on Figures 6.23 and 6.24. In this case, the maximum power flow on the GSP (Figure 6.23) refers to power import in every micro DG scenario and thus it is reduced when we move from no to high micro DG. The

impacts of micro DG installation on the demand profile of the distribution network in a winter weekday (Figure 6.24) are similar to the ones observed in the low load scenario.

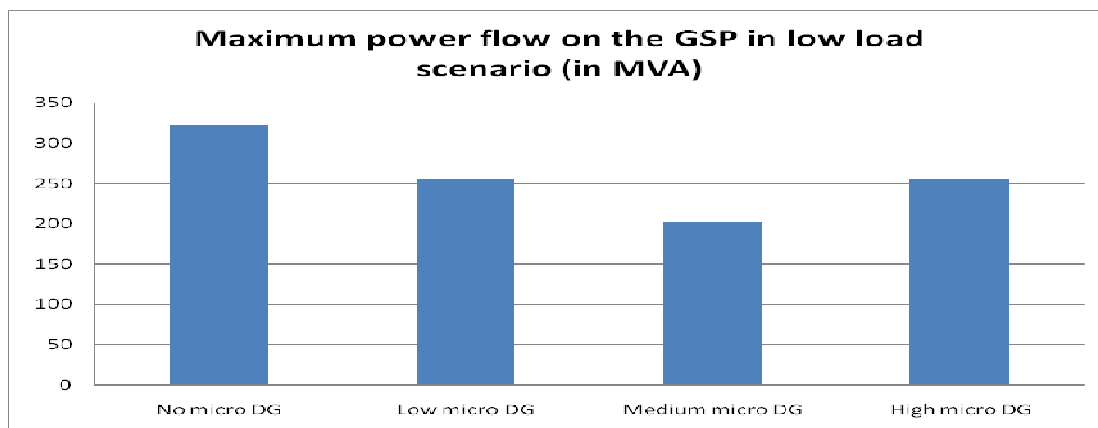


Figure 6.21. Maximum power flow on the GSP in low load scenario.

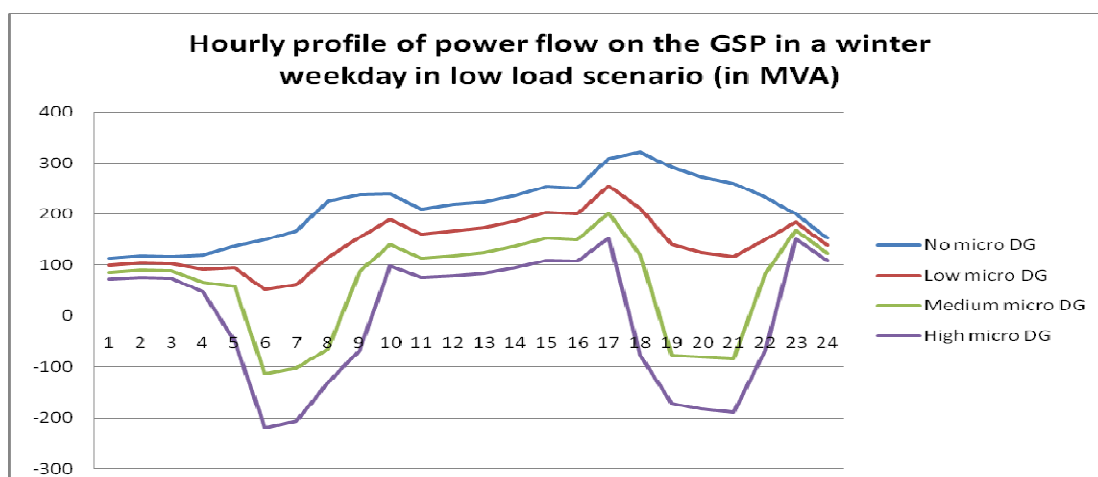


Figure 6.22. Hourly profile of power flow on the GSP in low load scenario.

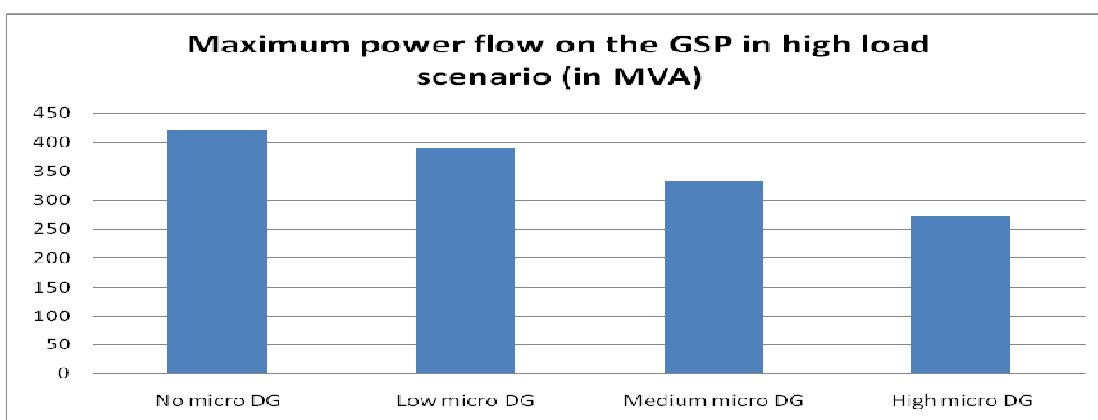


Figure 6.23. Maximum power flow on the GSP in the high load scenario.

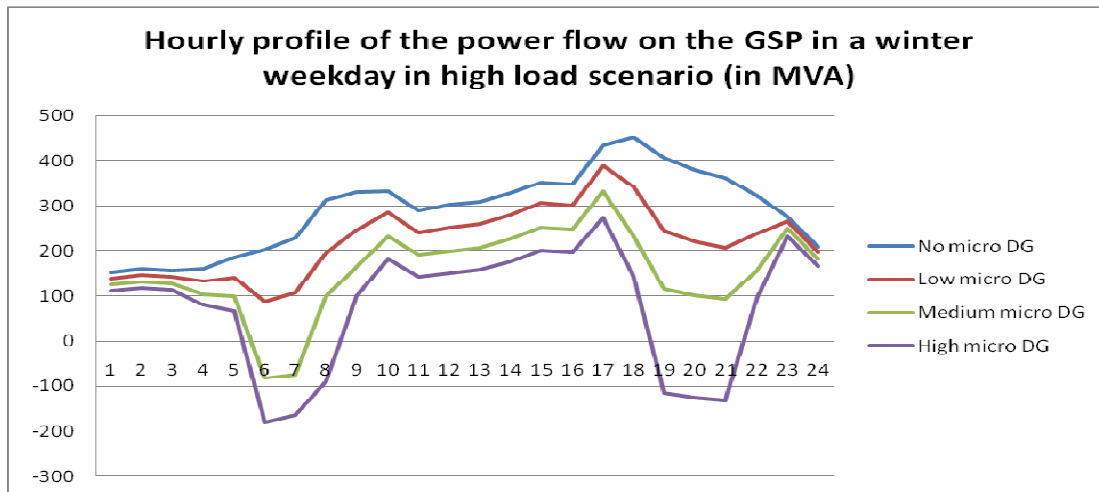


Figure 6.24. Hourly profile of the power flow on the GSP in high load scenario.

### 6.1.6 Environmental Benefits

As explained in detail in the main deliverable, the installation of micro DG results in  $CO_2$  emissions reduction because i) it reduces losses and ii) it displaces part of the central electricity production (micro CHP generators also displace part of the heat production of conventional boilers); the marginal plant model (presented in the main deliverable) and a parametric analysis (for different values of the emission factor of the marginal plant) is used for the calculation of this reduction (for simplicity reasons only for the optimal operating strategy, which is active management with tap changers in every micro DG scenario according to the results of section 6.1.4).

The  $CO_2$  emissions reduction (with respect to the no DG case) caused by micro CHP energy production (Figure 6.25), by micro PV energy production (Figure 6.26), by the reduction of losses (Figure 6.27) and the total one (Figure 6.28) for the low load scenario are presented below. We observe that the emissions reduction caused by local power generation (both CHP and PV generation) and losses reduction increases linearly with the emission factor of the marginal plant, as described by the relevant equations in the main deliverable. For a certain emission factor of the marginal plant, the emissions reduction due to CHP and PV production increases with the micro DG capacity (since larger capacity means larger local energy production, as depicted on Figure 6.20). On the other hand, the emissions reduction due to losses reduction is the highest in the medium micro DG scenario, since losses are the lowest in this case (as depicted on Figure 6.8). However, the total emissions reduction increases with the micro DG penetration since the greatest part of the total emissions reduction comes from micro CHP energy production. Similar trends are observed in the high load case.

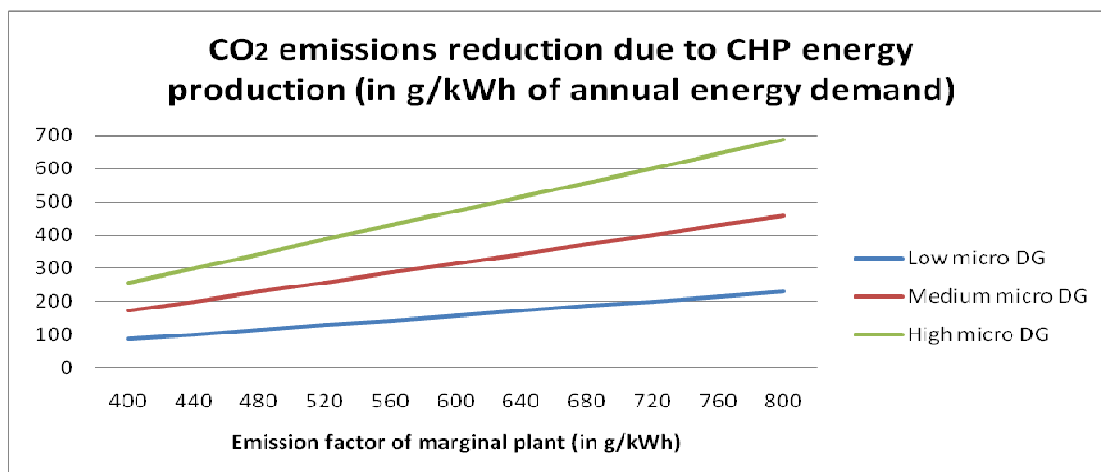


Figure 6.25. CO<sub>2</sub> emission reduction due to CHP energy production.

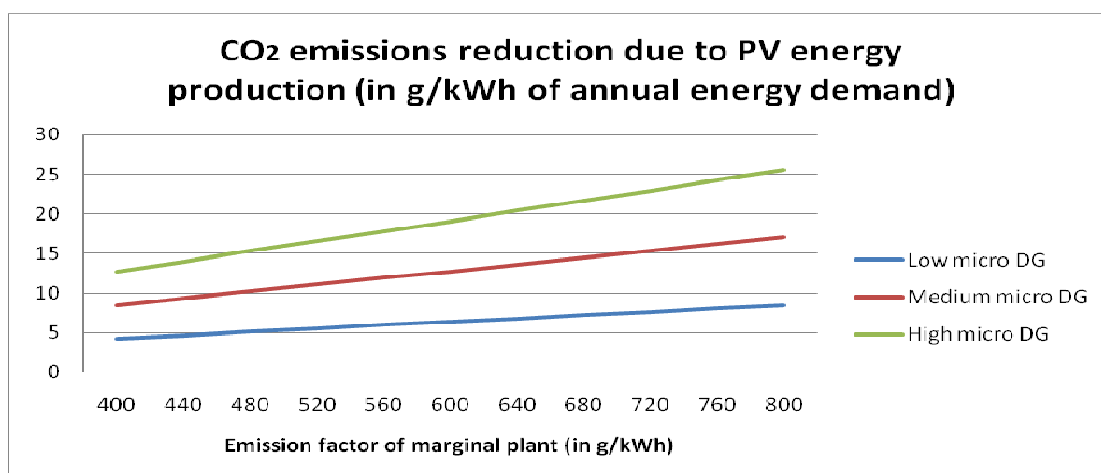


Figure 6.26. CO<sub>2</sub> emission reduction due to PV energy production.

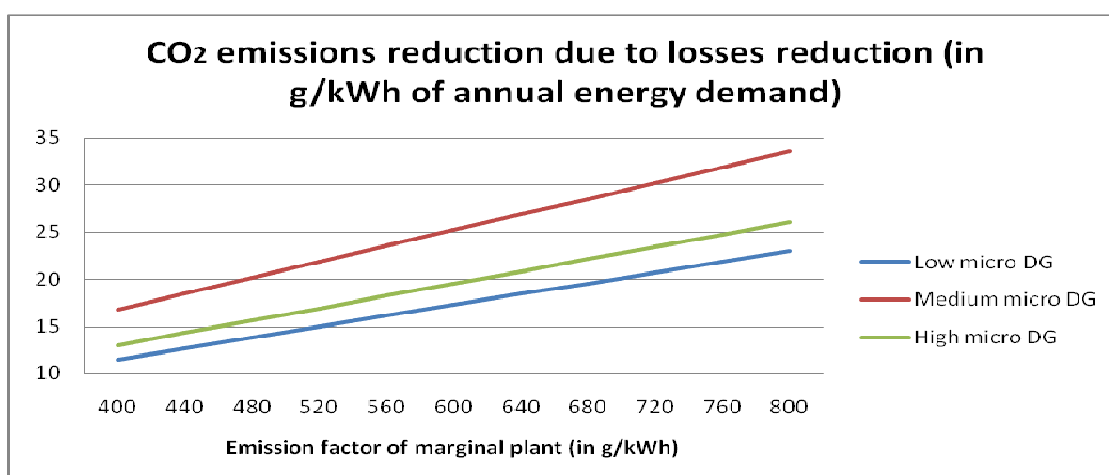
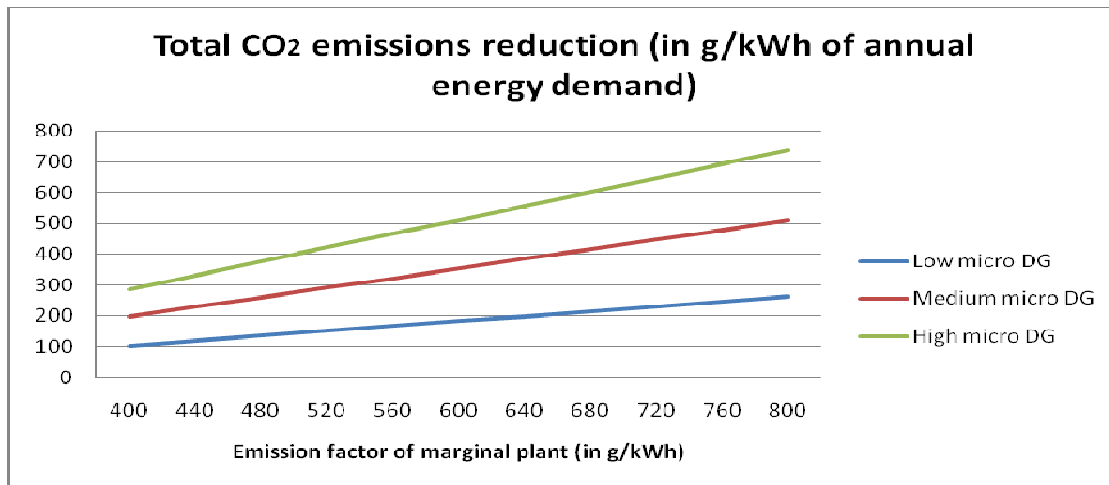


Figure 6.27. CO<sub>2</sub> emission reduction due to losses reduction.

Figure 6.28. Total CO<sub>2</sub> emission reduction.

### 6.1.7 Conclusion

Our analysis on the UK network shows that the whole required reinforcement in the low load scenario is related to **violations of voltage limits** at the **medium voltage levels** (11kV and 33kV), caused by demand (voltage drop); in the high load, **violations of both voltage and thermal limits** occur (again caused by demand) and reinforcement is needed in **every voltage level**. Since this reinforcement is driven by demand, the installation of **micro DG reduces reinforcement cost** (Figure 6.2 and Figure 6.5) -by mitigating the above mentioned voltage drop and thermal problems- and as the micro DG penetration increases, the reinforcement cost is reduced; in the low load case, no reinforcement is required with a high micro DG penetration. It is worth stressing that this beneficial impact of micro DG is not restricted in the voltage level it is connected, as it also extenuates the required reinforcement of higher voltage levels (Figure 6.4 and Figure 6.7). The deployment of **active management reduces further the reinforcement cost** (apart from the low load-high micro DG scenario), since the cost of implementing the active controls is much lower than the cost of replacing the feeders suffering from voltage problems. This benefit of active management becomes less apparent when the micro DG penetration increases and the demand decreases, as the emerging voltage drop problems become less severe. The active management strategy giving the lowest reinforcement cost under each of the possible demand-micro DG combinations (apart from the low load-high micro DG scenario) is **AM with tap changers**, because the voltage problems arising are severe enough to economically justify the installation of tap changers.

The installation of **micro DG reduces losses** at the network (and their cost) as part of the power required by the load is supplied locally and consequently the power flows from the GSP to the demand are reduced (Figure 6.21 and Figure 6.23); thus, as the micro DG penetration increases, the losses reduction with respect to the base case (no DG) becomes more significant (Figure 6.8 and Figure 6.12). However, after a certain point of increase, micro DG becomes higher than the load and **reverse power flows emerge**; if the reverse flows caused by a certain capacity of micro DG are significant, the installation of this

capacity will result in an **increase of losses**. This is the case in the low load-high micro DG scenario: significant reverse power flows emerge and the losses are higher than in the low load-medium micro DG scenario. **Losses under passive management are lower** because the feeders suffering from voltage problems are replaced with feeders of smaller resistance (which is not the case under active management); this difference becomes less apparent as micro DG penetration is increased and load is decreased, since the severity of the arising voltage problems is reduced (in the low load-high micro DG scenario, no reinforcement is required and thus the losses are the same under every strategy). Moreover since this difference is related to the way of resolving feeders' voltage problems, it does not affect the transformers' losses (Figure 6.9 and Figure 6.13).

Since micro DG reduces both the reinforcement cost and the cost of losses, it has a **beneficial impact on the total network cost** (Figure 6.16 and Figure 6.18). In the low load scenario, even though high micro DG penetration gives zero reinforcement cost, medium micro DG penetration is characterized by the lowest total network cost since it gives the lowest (cost of) losses; in the high load scenario, high micro DG penetration is characterized by the lowest total network cost because it gives both the lowest reinforcement cost and the lowest (cost of) losses. **Active management reduces further the total network cost**, because its positive impact on the reinforcement cost is much more significant than its negative impact on the (cost of) losses; more specifically, **active management with tap changers is the optimal strategy** in each scenario (apart from the low load-high micro DG scenario where no reinforcement is required and thus all the strategies are equivalent) because of its significant positive impact on reinforcement cost.

While in the low load scenario the **incremental benefit of micro DG** on the total network cost (value of the next kW of micro DG) decreases as its penetration increases for every operating strategy (Figure 6.17), in the high load scenario the **saturation effect** on this incremental benefit is observed (Figure 6.19) under passive management: it increases when we move from low to medium micro DG penetration (because the benefits from a low penetration are so limited that there is significant room for beneficial impacts from extra micro DG capacity) and it decreases when we move from medium to high micro DG penetration (because the benefits from a medium penetration are so significant that the room for beneficial impacts from extra micro DG capacity is limited). Furthermore, for the same micro DG penetration and the same operating strategy, this incremental benefit is higher in the high load scenario, since the emerging voltage and thermal problems are more severe and thus there is more room for beneficial effects of extra micro DG capacity.

Due to the fact that the foreseen capacity share and the average load factor of micro CHP generators is much higher than the respective parameters of micro PV generators, there is a huge difference between the micro CHP and the micro PV energy production (Figure 6.20). As a result, micro CHP generators have the main responsibility for the **alterations in the aggregate demand curve of the UK distribution network**: they move the whole curve downwards and they change its shape (as a result the time that the peak demand occurs in a winter weekday is changed) due to the characteristics of their generation profile (Figure 6.22 and Figure 6.24).

Finally, **micro DG reduces CO<sub>2</sub> emissions** since it reduces losses and it displaces part of the central electricity production (micro CHP generators also displace part of the heat production by conventional boilers). For a certain emission factor of the marginal plant of

central generation, the emissions reduction with respect to the base case (no DG) increases with the micro DG penetration and the most significant component of emissions reduction comes from the displacement of conventional boilers' heat and central electricity production by the energy production of micro CHP generators (Figure 6.25 to Figure 6.28).

## 7. Comparative Analysis

### 7.1 *Dynamic assessment of DG and AM based on partners' scenarios*

#### 7.1.1 *Introduction*

In this section, a comparison of the results acquired from our dynamic analysis on distribution networks of three different countries is carried out. More specifically, these three distribution networks are compared on the basis of the impacts of (the foreseen in each network) DG and the implementation of AM with respect to the base case (no DG and passive management) over the next 20 years. Our analysis on the distribution network of **Poland** has included the deployment of different operating strategies (passive management, active management without tap changers and active management with tap changers), since voltage problems emerge in this network; for simplicity reasons, only the results which correspond to the optimal operating strategy (the one giving the lowest total network cost) are presented, and thus the impact of AM is inherently included in the following results. Moreover, our analysis on the distribution network of **Germany** has showed that the installation of DG causes fault level problems and the cost of the required reinforcement depends on the available break rating headroom of the existing switchboards; for simplicity reasons, only the results which correspond to the worst case scenario (10% headroom) are presented.

#### 7.1.2 *Benefits related to reinforcement cost*

The reduction in the reinforcement cost by the installation of DG for the different distribution networks in each of the examined time windows is presented on Figure 7.1. We can observe that the installation of DG has different impacts on the reinforcement cost of different networks:

- i) DG has a very significant positive impact on the reinforcement cost of the **Polish** network, since most of the required reinforcement is driven by demand (thus there is ground for DG to mitigate the reinforcement cost) and its largest part is related to violations of voltage limits (thus there is ground for active management to mitigate the reinforcement cost)
- ii) DG has no impact on the reinforcement cost of the **Dutch** network since this network is so strong that no reinforcement is required without or with DG installed
- iii) DG has a marginal negative impact on the reinforcement cost of the strong **German** network in the time windows 2010-2015 and 2030-2040 since the installation of DG causes fault level problems and thus drives the replacement of

some switchboards; on the other hand, it has no impact on the reinforcement cost in the time windows 2015-2020 and 2020-2030

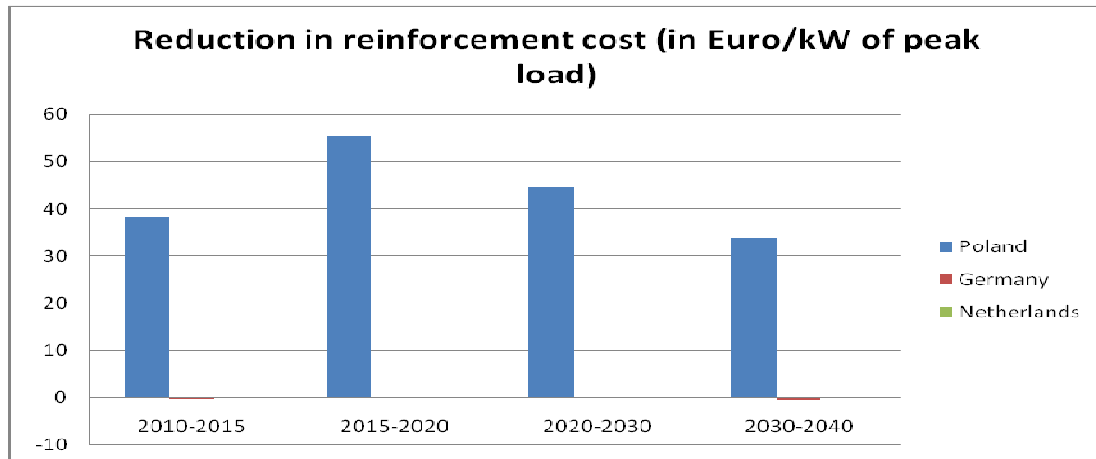


Figure 7.1. Reduction in reinforcement cost.

### 7.1.3 Benefits related to losses

The losses reduction by the installation of DG for the different distribution networks in each of the examined yearly snapshots is depicted on Figure 7.2. We can observe that the installation of DG has different impacts on the losses of different networks:

- i) DG has a positive impact on the losses of the **German** network, as part of the power required by the load is supplied locally and consequently the power flows from the GSP to the demand are reduced; this positive impact increases as years pass by, since DG penetration increases much faster than the demand and consequently greater part of the demand is supplied locally
- ii) DG has a negative impact on the losses of the **Dutch** network, since significant reverse power flows emerge in parts of the network where the installed DG capacity is relatively large in comparison with the load; this negative impact increases as the years pass by since DG penetration increases much faster than the demand and consequently the emerging reverse power flows become more significant
- iii) DG has a negative impact on the losses of the **Polish** network, because the strategy deployed in the DG case (active management without tap changers) is characterized by very high losses because it involves the connection of very large capacitive compensation which creates significant reverse power flows; this negative impact increases as the years pass by since this capacitive compensation increases faster than the demand and consequently the emerging reverse power flows become more significant



Figure 7.2. Losses reduction.

#### 7.1.4 Benefits related to total network cost

The reduction in total network cost (sum of the reduction in reinforcement cost and the reduction in the cost of losses) by the installation of DG for the different distribution networks in each of the examined time windows is presented on Figure 7.3. We can observe that the installation of DG has different impacts on the total network cost of different networks:

- i) DG has a significant positive impact on the total network cost of the **Polish** network, since its positive impact on reinforcement cost is extremely higher than its negative impact on (the cost of) losses
- ii) DG has a moderate positive impact on the total network cost of the **German** network, since its positive impact on (the cost of) losses is much higher than its marginal negative impact on reinforcement cost
- iii) DG has a marginal negative impact on the total network cost of the **Dutch** network, since it increases (the cost of) losses and it does not affect reinforcement cost

The network which is benefited the most by the installation of microgrids is the **Polish** one, where there is significant ground for DG to mitigate the required reinforcement. The incremental benefit of DG on the total network cost (value of the next kW of DG) for the different distribution networks in each of the examined time windows is presented on Figure 7.4; similar trends are observed here, with the highest value of DG being observed in the **Polish** network.

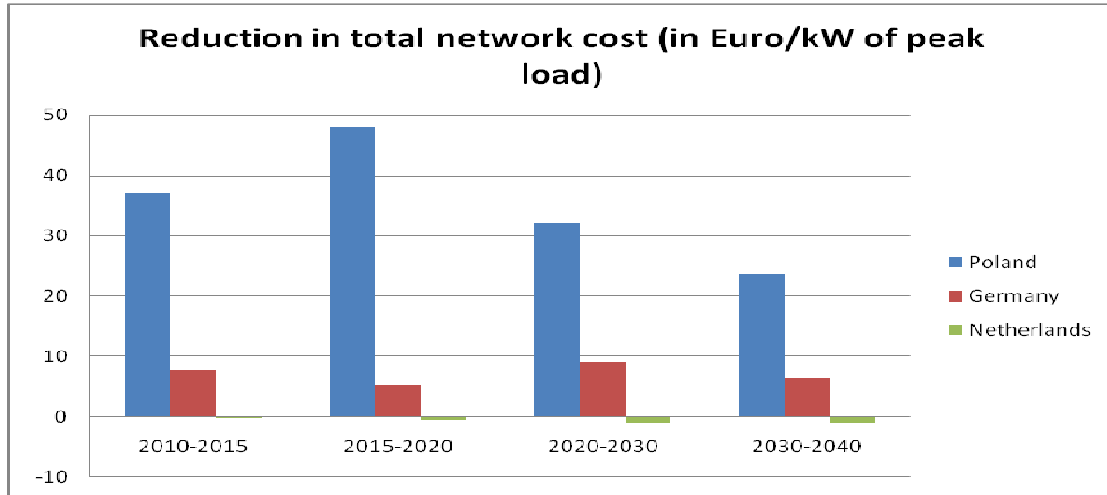


Figure 7.3. Reduction in total network cost (1).

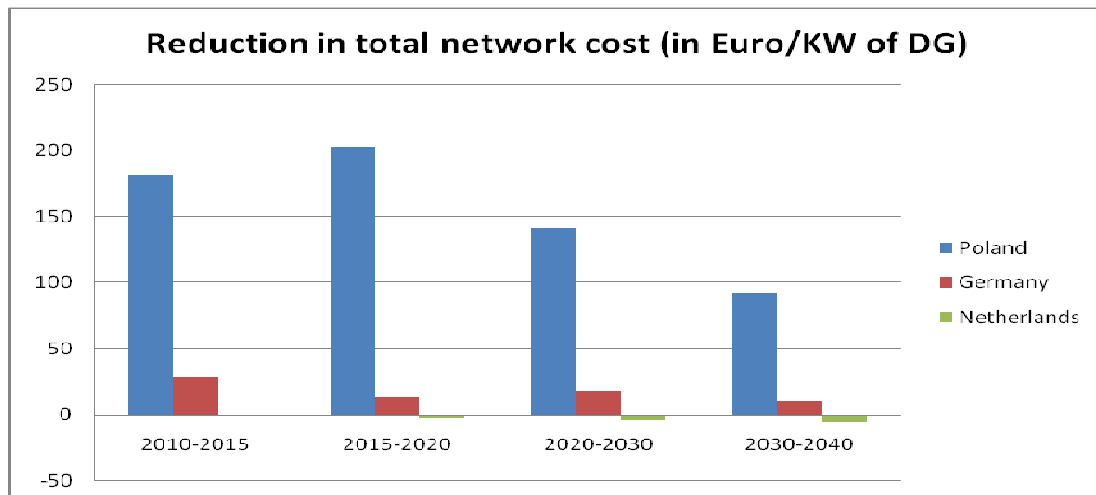


Figure 7.4. Reduction in total network cost (2).

### 7.1.5 Benefits related to local power generation

The percentage of annual energy demand covered by DG in the different distribution networks in each of the examined yearly snapshots is presented on Figure 7.5. We can observe that in every network this percentage increases throughout the years, as our partners foresee that DG penetration will increase faster than the demand. The differences observed between the different networks (for the same year) are due to their differences in: i) the foreseen DG capacity, ii) the load factor of DG, which depends on its composition (combined heat and power generators have much larger load factors than the renewable generators) and the load factors of each type of generators and iii) the foreseen annual energy demand. The network with the highest percentage in every year is the **German** one, because it is characterized by the largest DG capacity and CHP generators

constitute the main component of this capacity (while in the **Polish** and the **Dutch** network renewable generators have the greatest share in the installed DG capacity). Even though the **Polish** network exhibits the lowest percentage, it is characterized by the greatest benefit on total network cost by the installation of DG; this is evidence of the weakness of this network and the strength of the **German** and **Dutch** networks.

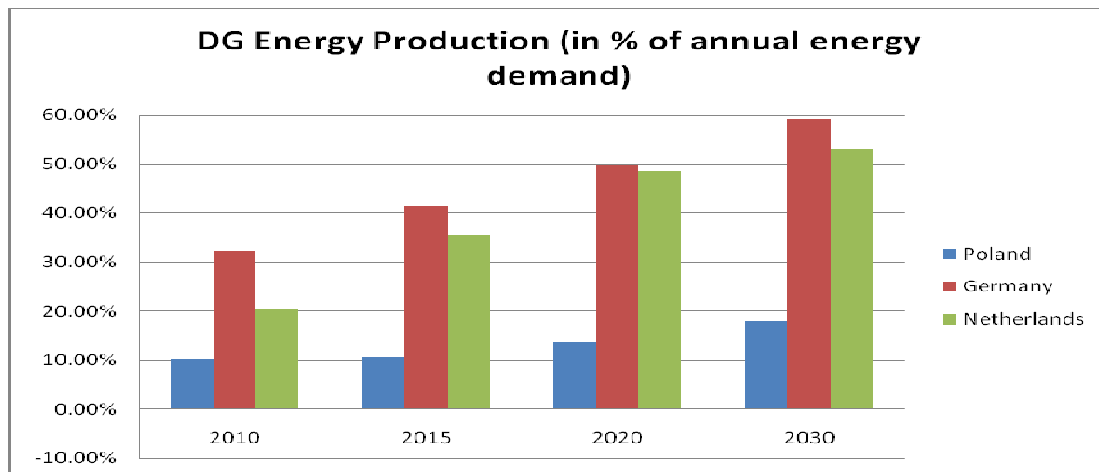


Figure 7.5. DG energy production.

### 7.1.6 Environmental benefits

The calculation of the total  $\text{CO}_2$  emissions reduction in each network was done for different values of the emission factor of the marginal plant of central generation  $\mu_{mp}$ ; for illustration purposes, we present this reduction for  $\mu_{mp}=600\text{g/kWh}$  (the average value in our analysis) for the different distribution networks in each of the examined yearly snapshots on Figure 7.6. We can observe that the installation of DG has always a positive impact on the total  $\text{CO}_2$  emissions because:

- i) in the **German** network, DG reduces emissions since it displaces part of the central electricity production (and part of the heat production of conventional boilers in case of CHP generators) and it reduces losses
- ii) in the **Polish** and **Dutch** networks, even though DG increases the emissions related to losses (since it increases losses), it decreases the total emissions due to the extremely higher positive impact of energy displacement

Since the impact of energy displacement on emissions is extremely higher than the respective impact of losses, emissions reduction in each network throughout the years follows the same increasing trend as the energy production (Figure 7.5) and the **German** network (which is characterized by the highest energy production) exhibits the highest emissions reduction in each of the examined snapshots.

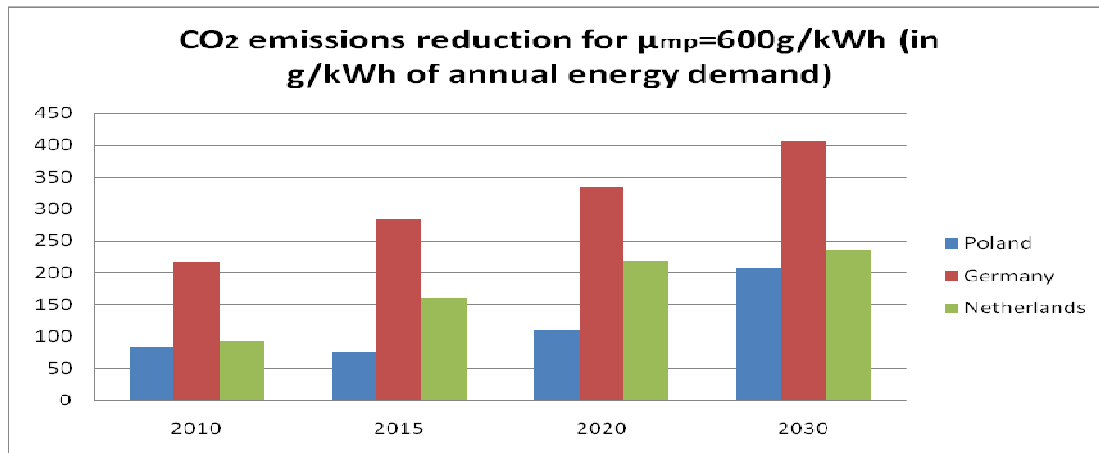


Figure 7.6. CO<sub>2</sub> emission reduction.

## 7.2 Parametric assessment of micro DG and AM on current distribution networks

### 7.2.1 Introduction

In this section, a comparison of the results acquired from our parametric analysis on distribution networks of five different countries is carried out. More specifically, these five distribution networks are compared on the basis of the impacts of micro DG and AM with respect to the base case (no micro DG and passive management). Our analysis on the distribution networks of **Poland**, **FYROM** and **UK** has included the deployment of different operating strategies (passive management, active management without tap changers and active management with tap changers), since voltage problems emerge in these networks; for simplicity reasons, only the results which correspond to the optimal operating strategy (the one giving the lowest total network cost) are presented, and thus the impact of AM is inherently included in the following results. Moreover, our analysis on the distribution network of **Germany** has showed that the installation of micro DG causes fault level problems and the cost of the required reinforcement depends on the available break rating headroom of the existing switchboards; for simplicity reasons, only the results which correspond to the worst case scenario (10% headroom) are presented.

### 7.2.2 Benefits related to reinforcement cost

The reduction in the annualized reinforcement cost by the installation of micro DG for the different distribution networks in the low and the high load scenario is presented on Figure 7.7 and Figure 7.8, respectively. We can observe that the installation of micro DG has different impacts on the reinforcement cost of different networks:

- i) in the **Polish, FYROM and UK** networks micro DG has a positive impact on the reinforcement cost since reinforcement is driven by demand (thus there is ground for micro DG to mitigate the reinforcement cost) and its largest part is related to violations of voltage limits (thus there is ground for active management to mitigate the reinforcement cost); the network which is benefited the most by the installation of micro DG in the low load scenario is the **Polish** one, while the greatest benefit by the installation of micro DG in the high load scenario is observed in the **UK** network
- ii) in the **Dutch** network micro DG has no impact on the reinforcement cost since this network is so strong that no reinforcement is required without or with micro DG installed
- iii) in the **German** network micro DG has a negative impact on the reinforcement cost since the installation of micro DG causes fault level problems and thus drives the replacement of some switchboards

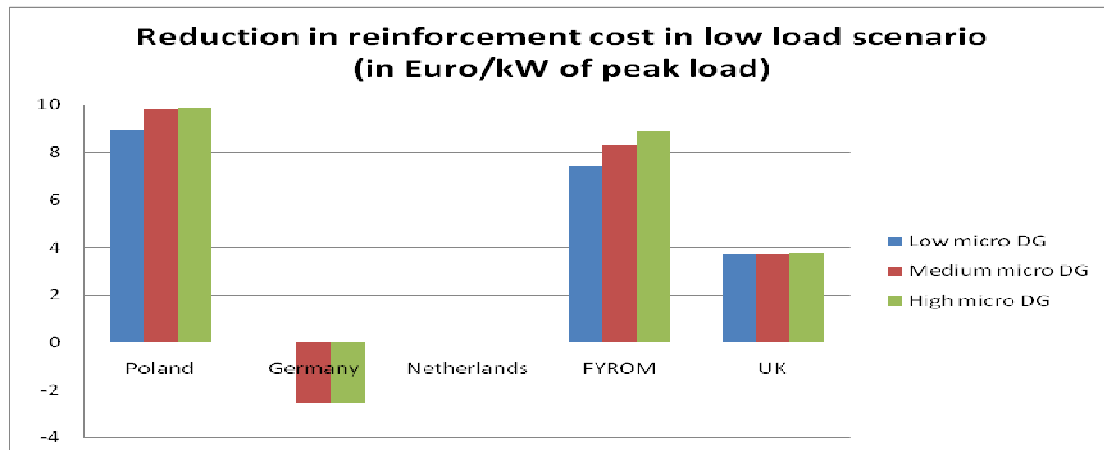


Figure 7.7. Reduction in reinforcement cost in low load scenario.

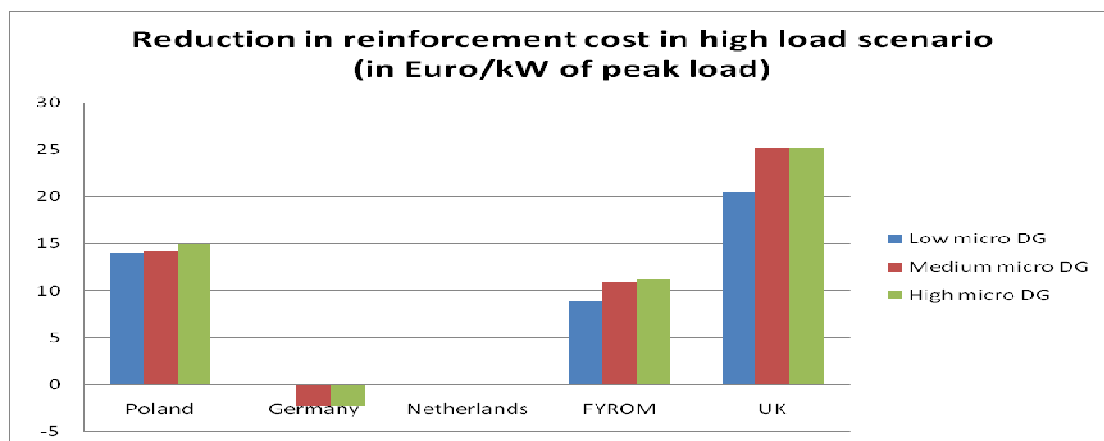


Figure 7.8. Reduction in reinforcement cost in high load scenario.

As expected, for a specific demand, the positive (**Poland, FYROM, UK**) and negative (**Germany**) impact of micro DG generally increases with its penetration.

### 7.2.3 Benefits related to losses

The losses reduction by the installation of micro DG for the different distribution networks in the low and the high load scenario is depicted on Figure 7.9 and Figure 7.10 respectively. We can observe that the installation of micro DG has always a positive impact on losses, as part of the power required by the load is supplied locally and consequently the power flows from the GSP to the demand are reduced; the only exemption is the high load – low micro DG scenario in the **Polish** distribution network, where the strategy deployed in the micro DG case (active management without tap changers) is characterized by very high losses because it involves the connection of very large capacitive compensation. We can also see that the losses reduction increases with the micro DG penetration; the only exemption is the low load scenario in the **UK** network where an increase from medium to high micro DG penetration results in significant reverse power flows and higher losses. Finally, while micro DG brings significant losses reduction (up to 60%) in the **Polish, FYROM** and **UK** networks, it does not have the same impact on the strong **German** and **Dutch** networks (the respective reduction is less than 15% in every scenario). The cost of losses follows similar trends since it is proportional to the amount of losses.

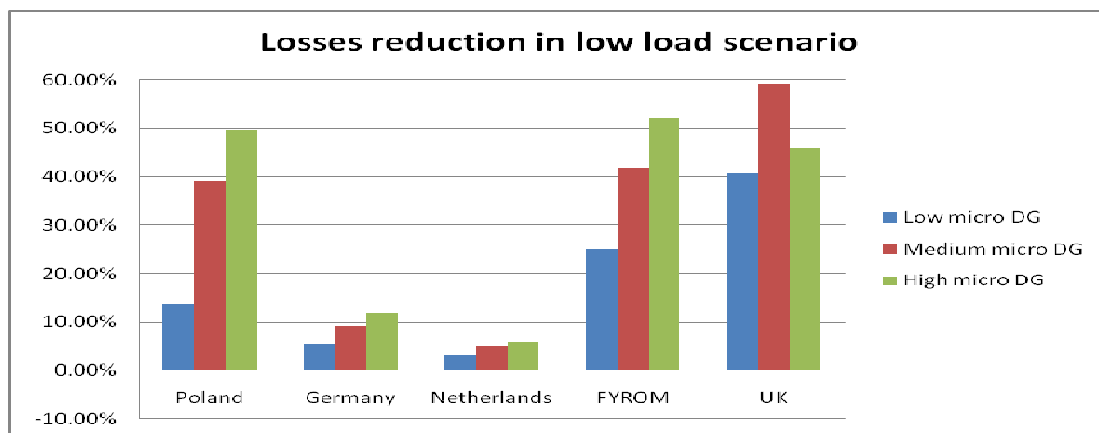


Figure 7.9. Losses reduction in low load scenario.

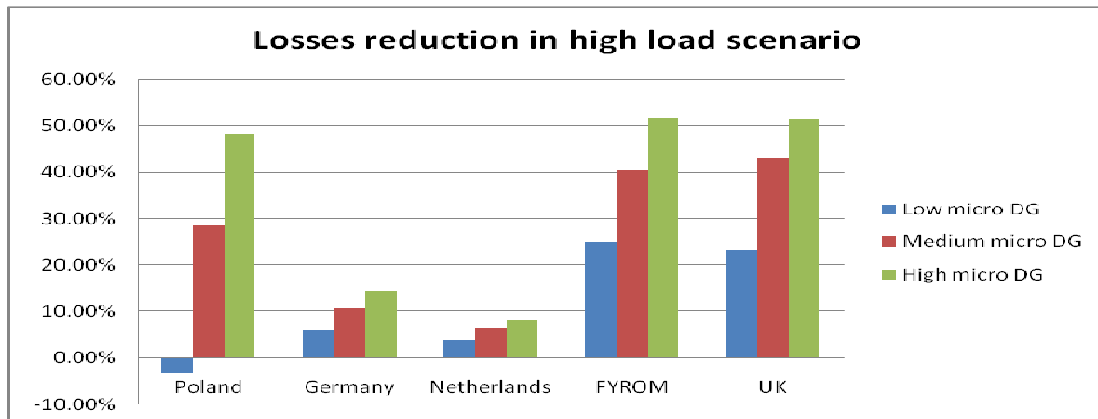


Figure 7.10. Losses reduction in high load scenario.

#### 7.2.4 Benefits related to total network cost

The reduction in total network cost (sum of the reduction in the annualized reinforcement cost and the reduction in the annual cost of losses) by the installation of micro DG for the different distribution networks in the low and the high load scenario is presented on Figure 7.11 and Figure 7.12, respectively. We can observe that the installation of micro DG has always a positive impact on the total network cost:

- i) in the **Polish**, **FYROM** and **UK** networks, micro DG reduces both the reinforcement cost (Figure 7.7 and Figure 7.8) and the cost of losses (since it reduces losses as shown on Figure 7.9 and Figure 7.10; the only exemption is the high load-low micro DG scenario in the **Polish** network but the increase in the cost of losses is extremely smaller than the reduction in the reinforcement cost),
- ii) in the **Dutch** network, micro DG reduces the cost of losses (since it reduces losses), while it has no impact on the reinforcement cost and
- iii) in the **German** network, even though micro DG has a negative impact on the reinforcement cost it has a much higher positive impact on the cost of losses (since it reduces losses).

Regarding the impacts of different micro DG penetrations, we can see that:

- i) in the **Polish** and **FYROM** networks, the total network cost is decreased when the micro DG penetration is increased, since both the reinforcement cost and the cost of losses follow the same trend,
- ii) in the **UK** network, the same trend is observed in the high load scenario; in the low load scenario however, even though the reinforcement cost is decreased when the micro DG penetration is increased, the medium micro DG penetration gives the optimal total network cost, since it results in much lower losses than the high penetration,

- iii) in the **Dutch** network, the total network cost is decreased when the micro DG penetration is increased, since the cost of losses follows the same trend and the micro DG penetration has no impact on the reinforcement cost and
- iv) in the **German** network, even though an increase in micro DG penetration causes an increase in reinforcement cost, it results in a much higher decrease in the cost of losses and thus in an increase in the total network cost.

A huge difference is observed between the benefits of micro DG on the strong **Dutch** and **German** networks (where micro DG does not reduce the reinforcement cost) and the weaker **Polish**, **FYROM** and **UK** networks (where micro DG reduces significantly the reinforcement cost). The network which is benefited the most by the installation of micro DG in the low load scenario is the **FYROM** one; in the high load scenario on the other hand, the greatest benefit from the installation of micro DG is observed in the **UK** network.

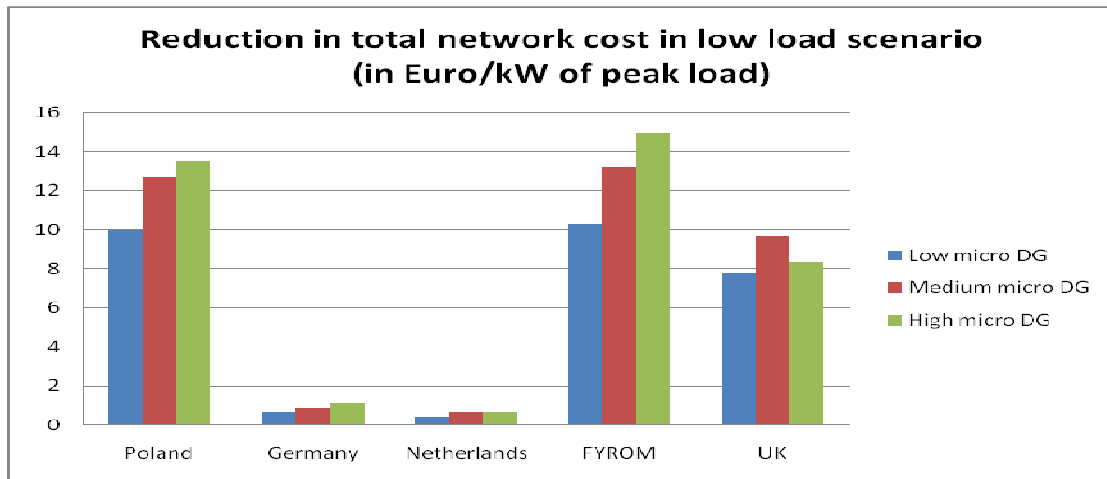


Figure 7.11. Reduction in total network cost in low load scenario (1).

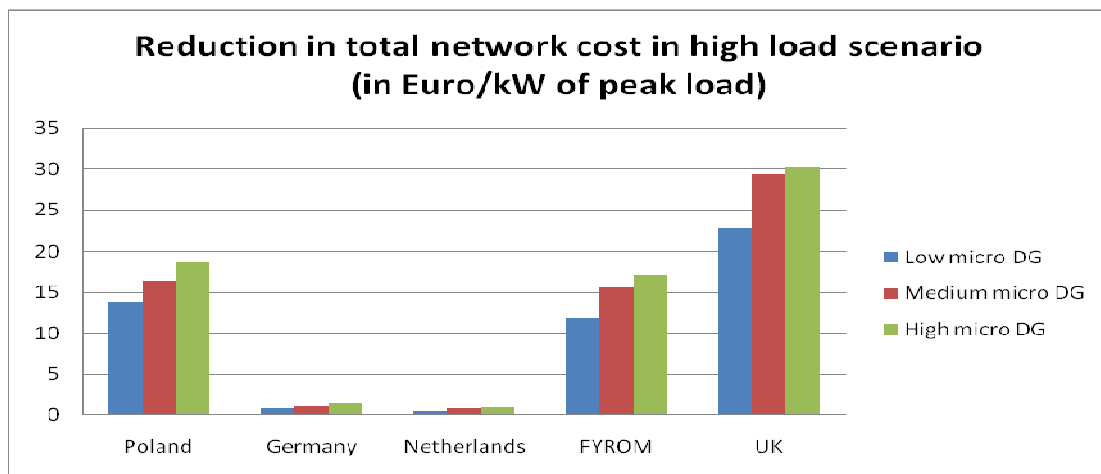


Figure 7.12. Reduction in total network cost in high load scenario (1).

The incremental benefit of micro DG on the total network cost (value of the next kW of micro DG) for the different distribution networks in the low and the high load scenario is depicted on Figure 7.13 and Figure 7.14 respectively. For each network, as the micro DG penetration is increased (for a specific level of demand) and as the demand is decreased (for a specific level of micro DG penetration), the available room for beneficial effects of extra micro DG capacity is reduced and thus the value of the next kW of micro DG is decreased. The networks with the highest value of micro DG in the low and the high load scenario are the **Polish** and the **UK** network respectively.

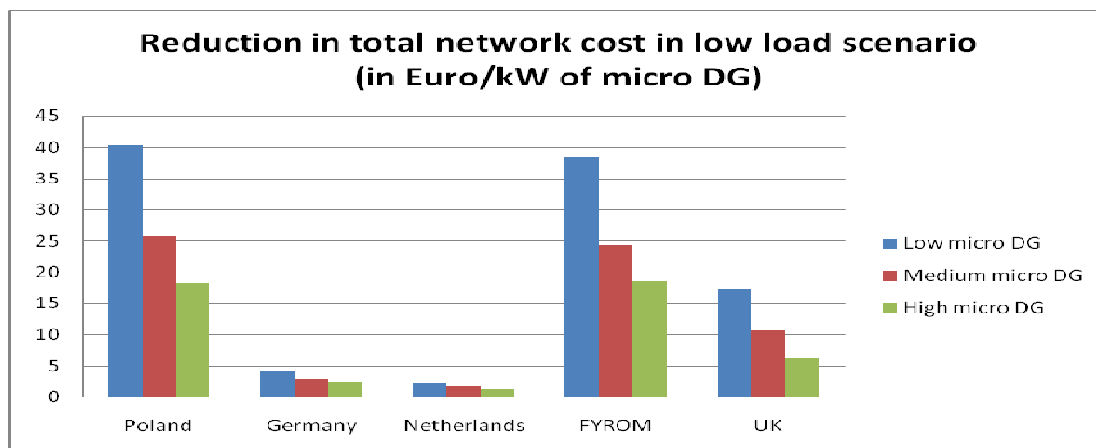


Figure 7.13. Reduction in total network cost in low load scenario (2).

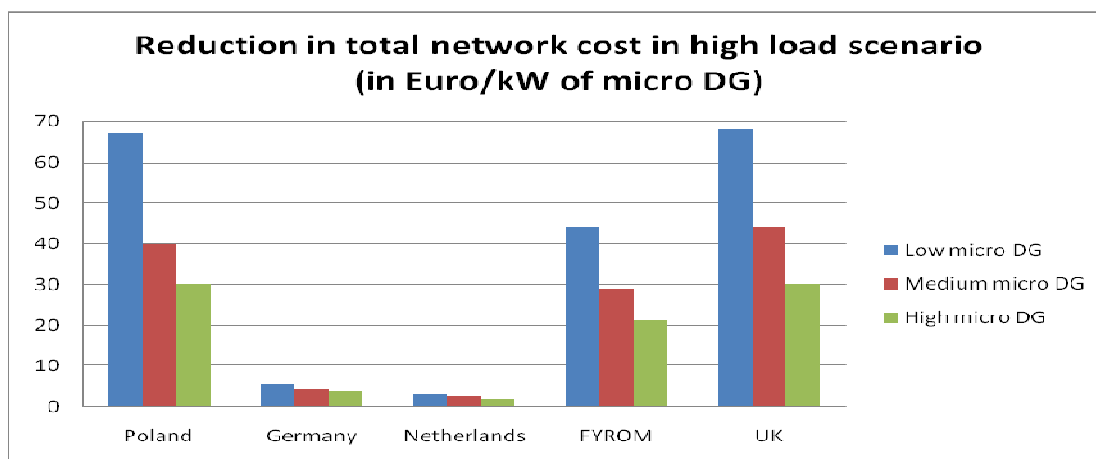


Figure 7.14. Reduction in total network cost in high load scenario (2).

### 7.2.5 Benefits related to local power generation

The percentage of annual energy demand covered by micro DG in the different distribution networks in the low and the high load scenario is depicted on Figure 7.15 and Figure 7.16 respectively. As expected, for a specific network, this percentage is increased as the micro DG penetration is increased (for a specific level of demand) and is decreased

as the demand is increased (for a specific level of micro DG penetration). The differences observed between the different networks (for the same load-micro DG scenario) are due to their differences in: i) the installed micro DG capacity, ii) the load factor of micro DG, which depends on its composition (CHP and PV capacity shares) and the load factors of individual micro CHP and micro PV generators and iii) the annual energy demand. The network with the highest percentage in every scenario is the UK one, because it is characterized by the largest installed micro DG capacity and the largest share of CHP generators (which have larger load factors than the PV generators in every country).

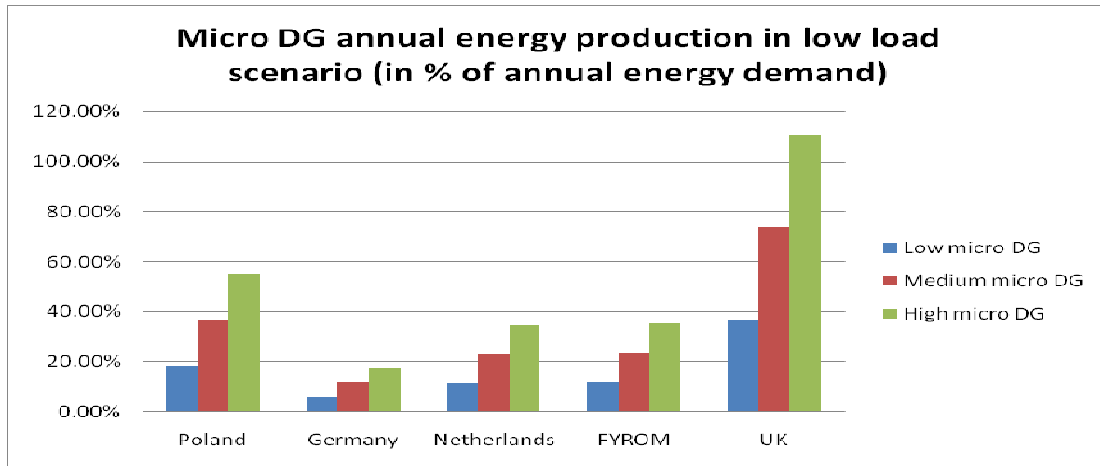


Figure 7.15. Micro DG annual energy production in low load scenario.

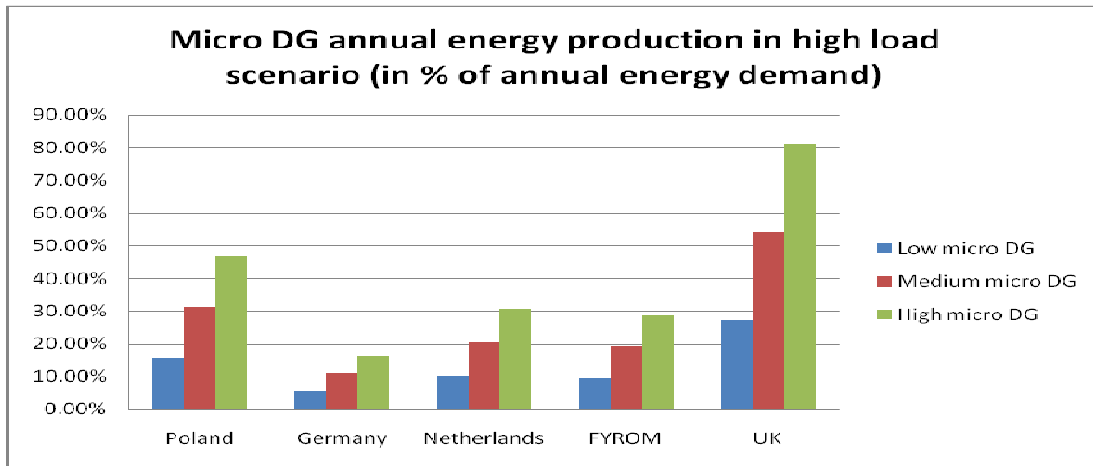


Figure 7.16. Micro DG annual energy production in high load scenario.

### 7.2.6 Environmental benefits

The calculation of the total  $CO_2$  emissions reduction in each network was done for different values of the emission factor of the marginal plant of central generation  $\mu_{mp}$ ; for illustration purposes, we present this reduction for  $\mu_{mp}=600g/kWh$  (the average value in

our analysis) for the different distribution networks on Figure 7.17 and Figure 7.18 (for the low and the high load scenario respectively). We can observe that the installation of micro DG has always a positive impact on  $CO_2$  emissions, since it displaces part of the central electricity production (and part of the heat production of conventional boilers in case of micro CHP generators) and it reduces losses. Moreover, we can see that the emissions reduction is increased when the micro DG penetration is increased, since the energy production from micro DG and the losses reduction become more significant. The impact of energy displacement on  $CO_2$  emissions is extremely higher than the respective impact of losses reduction in every distribution network. The most significant emissions reduction is observed in the UK network, since this network is characterized by the highest energy production from micro DG (for the reasons explained in the previous section).

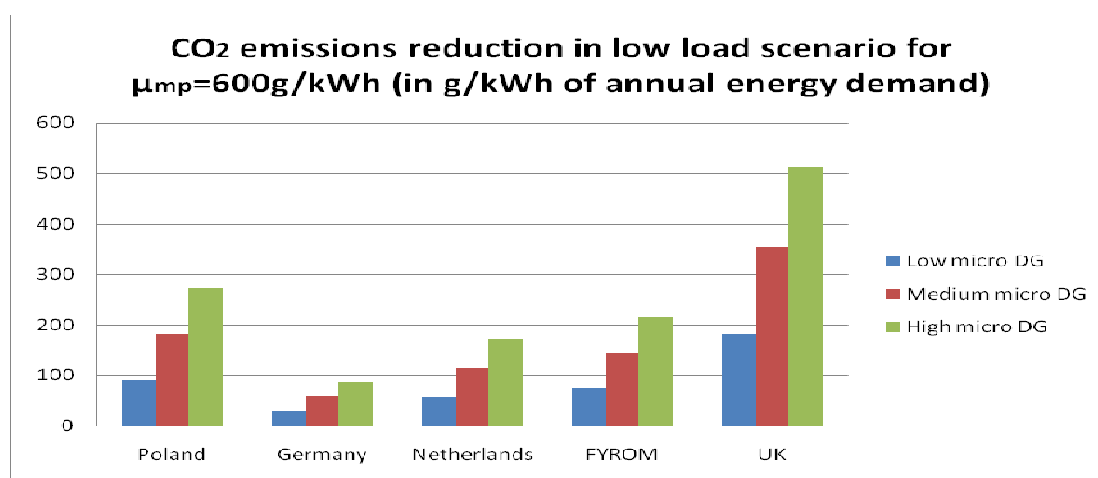


Figure 7.17. CO<sub>2</sub> emission reduction in low load scenario.

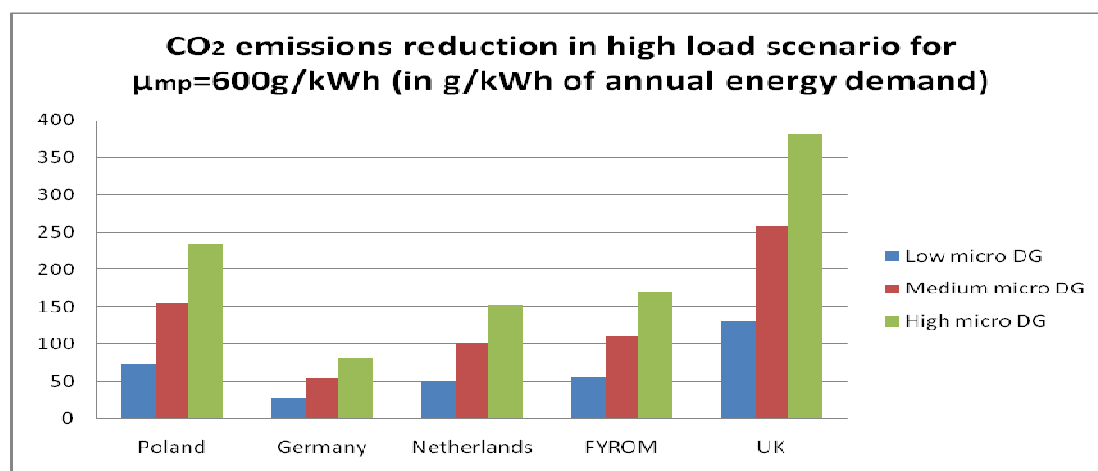


Figure 7.18. CO<sub>2</sub> emission reduction in high load scenario.

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