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DG3. Report on the technical, social, economic, and environmental benefits provided by Microgrids on power system operation

Annex 3 – Microgrid Scheduling via Genetic Algorithm and Heuristic Search

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Content

Abbreviations

AAT	Approximated Annual Trend Curve
AcP	Accumulated Active Power
AcQ	Accumulated Reactive Power
AOP	Annual Overloading Probability
AR	Autoregressive Method
ARMA	Autoregressive Moving-Average Method
AUoS	Avoided Use of System Charge
AVC	Automatic Voltage Control
BS	Branched Section
C&I	Commercial and Industrial
CDF	Cumulative Distribution Function
CHP	Combined Heat and Power
CNV	Constant Node Voltage
DER	Distributed Energy Resources
DEV	Decoupled Equivalent Variables
DG	Distributed Generation
DSM	Demand Side Management
DSO	Distribution System Operator
EEX	European Energy Exchange AG
EHV	Extra High Voltage
EMP	Equivalent Meshing Power
ETS	Emission Trading System
FA	First After Branch
FACTS	Flexible Alternating -Current Transmission System
FIT	Feed-in Tariff
FLH	Full Load Hours
G/L	Generation / Load
GHG	Green House Gas
HDR	Hard-Dry-Rock
HV	High Voltage
ICV	Instantaneous Coefficient of Variation
IPM	Iterative Power Modification
IPP	Independent Power Producer
IPVM	Iterative Power and Voltage Modification
IVM	Iterative Voltage Modification
LB	Last Before Branch
LD	Loss Reduction Credit (Loss Difference)
LF	Load Flow
LFEA	Load Flow Estimation Algorithm
LNL	Line-Node-Load Element
LR	Loss Ratio
LTSN	Left-Truncated Standard Normal Distribution
LV	Low Voltage
MA	Moving-Average Method
MS	Main Section
MV	Medium Voltage
NPV	Net Present Value
O&M	Operation and Maintenance
ORG	Original Curve
PBTVE	Power-Based Transformer Voltage Estimation
PD	Peak Reduction Credit (Peak Difference)
PDF	Probability Distribution Function
PLF	Probabilistic Load Flow

PR	Peak Ratio
PV	Photovoltaic
RCV	Relative Coefficient of Variation
RDA	Daily Average Value
RES	Renewable Energy Sources
RHV	Relative Hourly Value
RTSN	Right-Truncated Standard Normal Distribution
SCL	Scale Factor
SER	Simulated Error Curve
SHP	Small Hydro Plant
SIM	Simulated Curve
SMO	Smoothed-Out Annual Curve
SPE	Starting Power Estimation
SVE	Starting Voltage Estimation
T&D	Transmission and Distribution
TGC	Tradable Green Certificates
TLTN	Translated Left-Truncated Normal Distribution
TSN	Truncated Standard Normal Distribution
TSO	Transmission System Operator
USC	Use of System and Connection Charges
VNV	Varying Node Voltage
VPP	Virtual Power Plant
WT	Wind Turbine

Chapter 1 Optimized Scheduling of Microgrids

Overview of the Microgrid Scheduling Task

From Traditional Unit Commitment to the Microgrid Scheduling Problem

The daily operation of a Microgrid is heavily influenced by a multitude of economical and technical factors raised by both micro-sources (MS) and distribution network properties. Thus active management of MS output is needed to achieve a least-cost solution while satisfying all technical requirements, which can be generally seen as a downsized version of the unit commitment and economic dispatch problem that is traditionally applied to large central generators only. However, some special features of distribution network have introduced further restrictions as well as simplifications to this classic optimization task, which should be dealt with extra care accordingly.

Early introduction of the term 'Unit Commitment' (UC) to power system operation was inspired by the economic motive of electricity industry, serving mainly to minimize the total cost of operating a number of generators to satisfy predicted load demand of a certain period (typically a day or a week). Economic Dispatch (ED), on the other hand, is generally defined as a sub-routine of UC task aimed at locating optimal active / reactive power outputs of generators at a specific instance with prescribed switching states.

Mathematically, the UC-ED task can be described as a combinatorial optimization problem with a nonlinear solution space, which is in general way too complex to be tackled with exhaustive search methods. Thus both analytical and metaheuristic approaches have been developed in the past decades to handle the UC-ED problem; among them the following choices are most popular:

- Priority List [5]
- Lagrange Relaxation [13] [15] [17]
- Genetic Algorithm [9] [10] [12] [14] [26] [28] [29] [31] [37] [41]
- Evolutionary Algorithm [11] [16]
- Simulated Annealing [18] [39]
- Particle Swarm Optimization [38]
- Mixed Integer Linear / Quadratic Programming [17] [19] [40]
- Dynamic Programming [34]
- Tabu Search [24] [30]
- Hopfield / Artificial Neural Network [25] [35]
- Ant Colony Search Algorithm [5]

It can be seen from the number of cited literature that genetic algorithm (GA) appears to be one of the most mature and widely-adopted metaheuristic approaches applied to the UC-ED problem. Thus in scope of this study, GA will be used as a reference solution to the Microgrid scheduling task.

In comparison with unit commitment problem on transmission level, the Microgrid scheduling task features the following major differences:

(1) Microgrids are normally constructed from concurrent LV distribution networks, which are normally radial or weakly-meshed and likely subject to technical problems such as over-/under-voltage or overloading when load / generation condition is changed.

(2) A complete formulation of Microgrid scheduling task includes modeling of storage dispatch, demand side management (DSM), and RES control measures (such as peak generation cut and reactive power control), while the traditional unit commitment problem faces none of them.

(3) A Microgrid might contain a considerable amount of RES units in it, which contribute significantly to power variations and make it much more difficult to produce accurate day-ahead schedules based on data forecasts.

The first issue listed above relates to the fact that Microgrids are inherently more fragile than HV / EHV transmission networks, which means unregulated operation of a large MS unit could easily cause technical problems in a weak Microgrid—which is apparently not the case for a transmission network with multiple power plants. The diversity of MS type and size, in the mean time, also makes it difficult to apply some traditional control methods adopted for transmission networks such as frequency control and PV operation mode for generators. Consequently, such limitations make the Microgrid scheduling task a more grid-constrained problem than traditional UC-ED formulations.

The second issue above introduces two major modeling complexities to the Microgrid scheduling task: (1) The scheduling task views all components of a Microgrid as a whole and attempts to arrive at a global optimum that delivers the best compromised result to all relevant entities, which proves to be difficult to implement within a single optimization platform due to varied physical and mathematical models used for different Microgrid components—e.g. multi-DG optimization at single time point can be easily achieved by OPF, while storage dispatch is most directly solved under single-unit, all-day consideration. (2) Both continuous (such as storage output) and discrete (such as on/off states of DG and DSM-controlled loads) decision variables exist, while in addition not all objective functions (such as storage usage cost) and constraints (such as line thermal loading) can be expressed as continuous linear or quadratic formulations, which causes the solution space of Microgrid scheduling task to be non-convex and forbids direct application of classical mathematical programming techniques.

The third issue above conveys the extra modeling complexities from uncertainty of MS output forecasts. In a traditional UC-ED problem, uncertainties stem mainly from load forecast errors at MV or even HV level, which are generally small and can be easily modeled as decoupled Gaussian variables. However, both smaller load sizes at LV level (thus higher variations) and addition of RES units to the MS assortment will significantly increase the amount of inter-correlated stochastic information in Microgrid scheduling task and makes normal stochastic programming techniques no longer applicable.

Microgrid Philosophies: Grid-Connected and Islanded Configurations

In the previous EU project 'Microgrids: Large Scale Integration of Micro-Generation to Low Voltage Grids', two market policies have been introduced to the Microgrid operation task: 'good citizen' and 'ideal citizen' models [5]. Both models assume Microgrids to be connected to external networks, and their difference lies mainly in the fact that a 'good citizen' Microgrid keeps its total reactive power at zero and sells electricity when prices are high, while an 'ideal citizen' Microgrid can sell and buy active and reactive power to / from external grids [5].
Due to difficulties of pricing reactive power (no implemented trading scheme so far), the reactive power demand or export of a Microgrid will not be modeled with any economic value in scope of this study. In the mean time, the number of operation policies for a Microgrid can be extended from two to four via change of grid-connection condition and grid control perspectives, as shown by Table 1-1.

<table>
<tr><th></th><th>Without Grid</th><th colspan="3">With Grid</th></tr>
<tr><th></th><th></th><th colspan="2">Top-down</th><th>Bottom-up</th></tr>
<tr><th></th><th>'True Island'
(Preset to zero)</th><th>'Econ-Island'</th><th>'Tech-Island'
'Good Citizen'</th><th>'True Exchange'
'Ideal Citizen'</th></tr>
<tr><td>P of Microgrid</td><td>Autonomous</td><td>Preset Control</td><td>Free Exchange</td><td>Free Exchange</td></tr>
<tr><td>Q of Microgrid</td><td>Autonomous</td><td>Free Exchange</td><td>Preset Control</td><td>Free Exchange</td></tr>
<tr><td rowspan="2">Features</td><td>Expensive;
Independent from grid;
Large storage;</td><td>Costly;
Economically independent;
Large storage;</td><td>Economic;
Can be seen as a VPP in total;
Small storage;</td><td>Most economic;
Total dependence on external grid;
Small/no storage;</td></tr>
<tr><td colspan="2">Self-sufficient supply of active power requires high storage capacity and forecast accuracy;</td><td colspan="2">Could lead to low utilization rates of MG (mostly as peak support) if they are not economically competitive;</td></tr>
<tr><td>Application</td><td>Temporary or permanent island operation</td><td>Microgrid only need Q from external grid</td><td>Whole Microgrid can participate in market as a VPP</td><td>Under economic operation mode or daily routine</td></tr>
</table>

Table 1-1 A List of Microgrid Operation Policies

In Table 1-1, Microgrid operation policies are differentiated according to (1) whether or not it is connected to an external grid, (2) if Microgrid operation has to conform to preset energy import / export levels (top-down perspective) or not (bottom-up perspective), (3) policies for controlling active and reactive power outputs of a Microgrid. Table 1-1 clearly indicates that the 'good citizen' model can be described as a 'technical island' in which only active power exchange between Microgrid and external network is allowed, while the 'ideal citizen' model corresponds to a 'true exchange' scenario where a Microgrid can freely exchange both active and reactive power with external network. In addition, Table 1-1 also introduces two new policies for Microgrid operation: 'economic island' and 'true island', while the later option corresponds to a physical island with no external grid.

Economic, Technical, and Environmental Concerns of a Microgrid

In the process of Microgrid operation, multiple objectives can be defined and pursued—which can be summarized in general as economic, technical, and environmental aspects. When a Microgrid is operated under economic motive, it will attempt to maximum profits from energy trading with minimum consideration of physical performance of the distribution grid it resides in. When a Microgrid is operated under technical motive, it will try to minimize total network losses from its control region and maintain network constraints such as voltage and device loading etc. within check. When a Microgrid is operated with pure environmental incentive, its sole operational aim will be the minimization of per-kWh GHG emission for electrical consumptions within it. Therefore, in order to arrive at an appropriate balance of interests from all network entities, compromise has to be made so as to simultaneously cover all these three aspects. In Figure 1-1, this multi-objective scheduling problem is illustrated in detail.

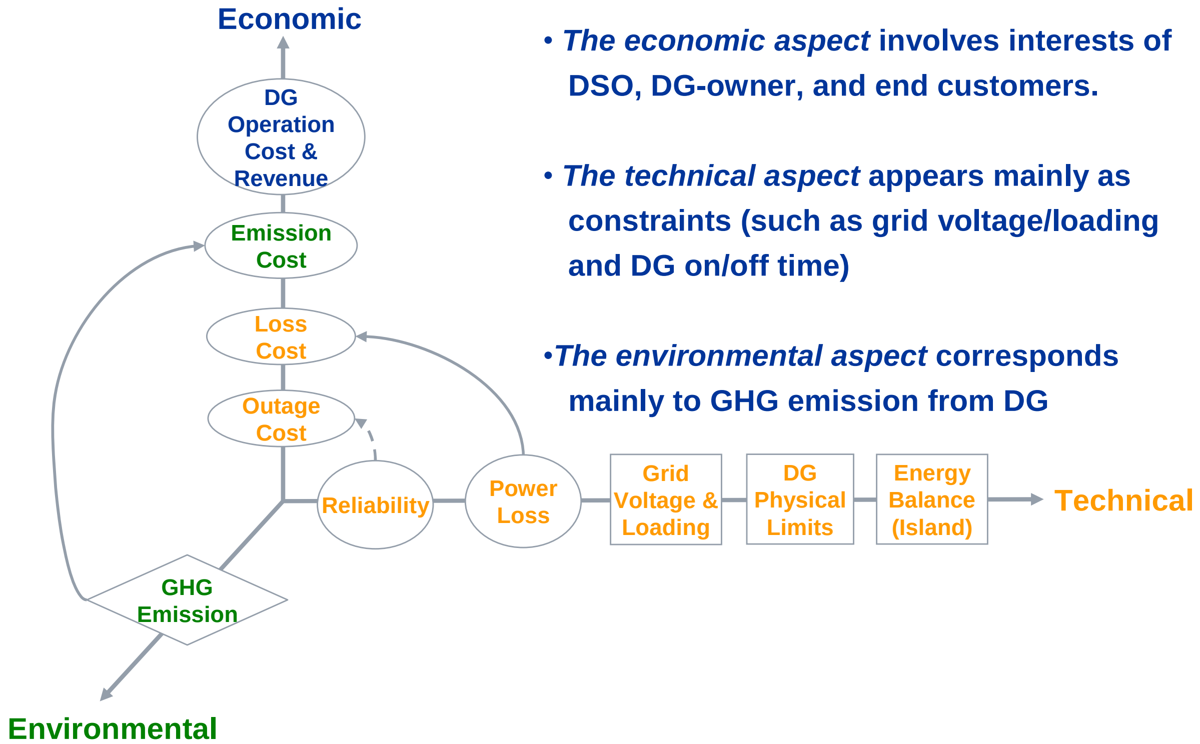

Figure 1-1 Layout of the Multi-Objective Microgrid Scheduling Task

One important notion should be emphasized concerning the concept of 'Microgrid' used in scope of this study: a Microgrid is viewed as a grouped entity that consists of loads (customers), MS units (energy producers or suppliers), as well as distribution network itself (local DSO). Thus the economic interest of a Microgrid can be seen as the total social cost or profit of maintaining its daily operation, which is mathematically equivalent to the sum of external cash flows to or from a Microgrid (while all internal cash flows are ignored). Similarly, the technical interest of a Microgrid will cover concerns of customers (supply reliability), MS operators (MS physical constraints) and DSO (grid performance). Environmental interest of a Microgrid can be most conveniently expressed as total (or per kWh) GHG emission level for supplying its internal (and potentially external) loads.

In Figure 1-2, the economic Microgrid operation mode is graphically illustrated. Notably, this economic mode tends to favor MG interests alone instead of the entire Microgrid.

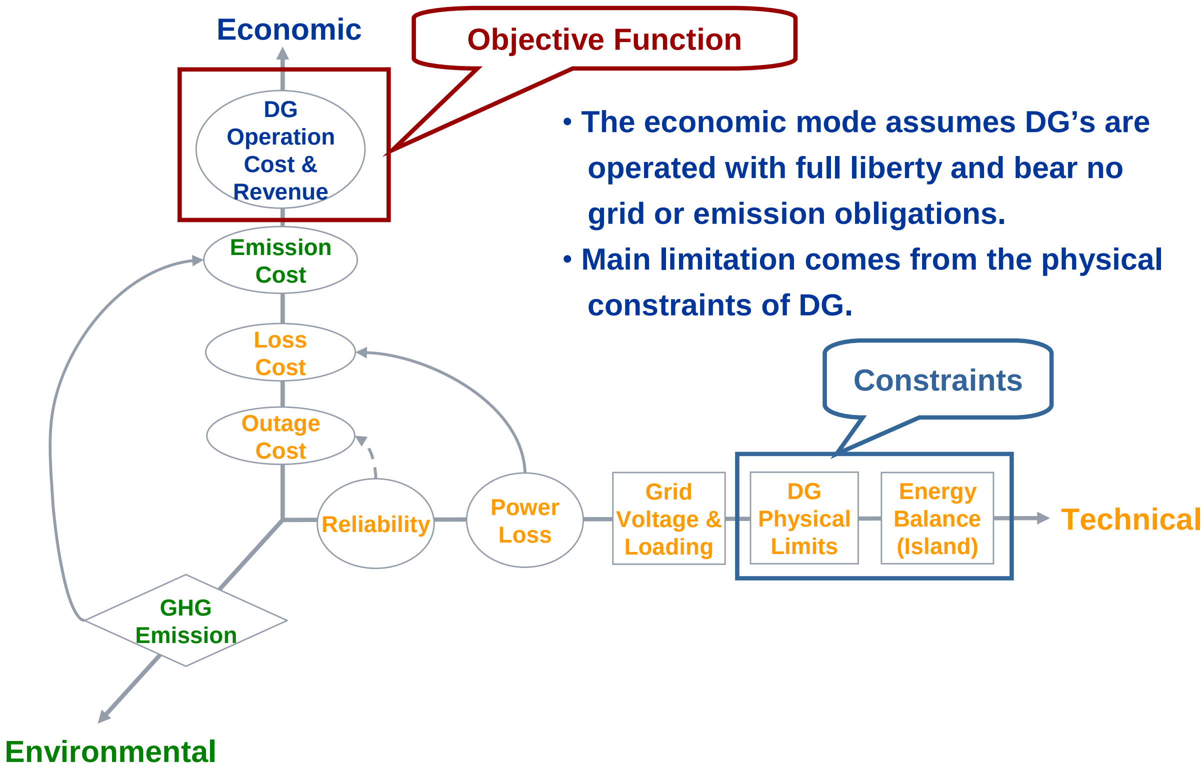

Figure 1-2 Economic Mode of Microgrid Operation

In Figure 1-3, the technical Microgrid operation mode is graphically illustrated. Obviously this mode is heavily DSO-oriented and only seeks to maximize grid performance.

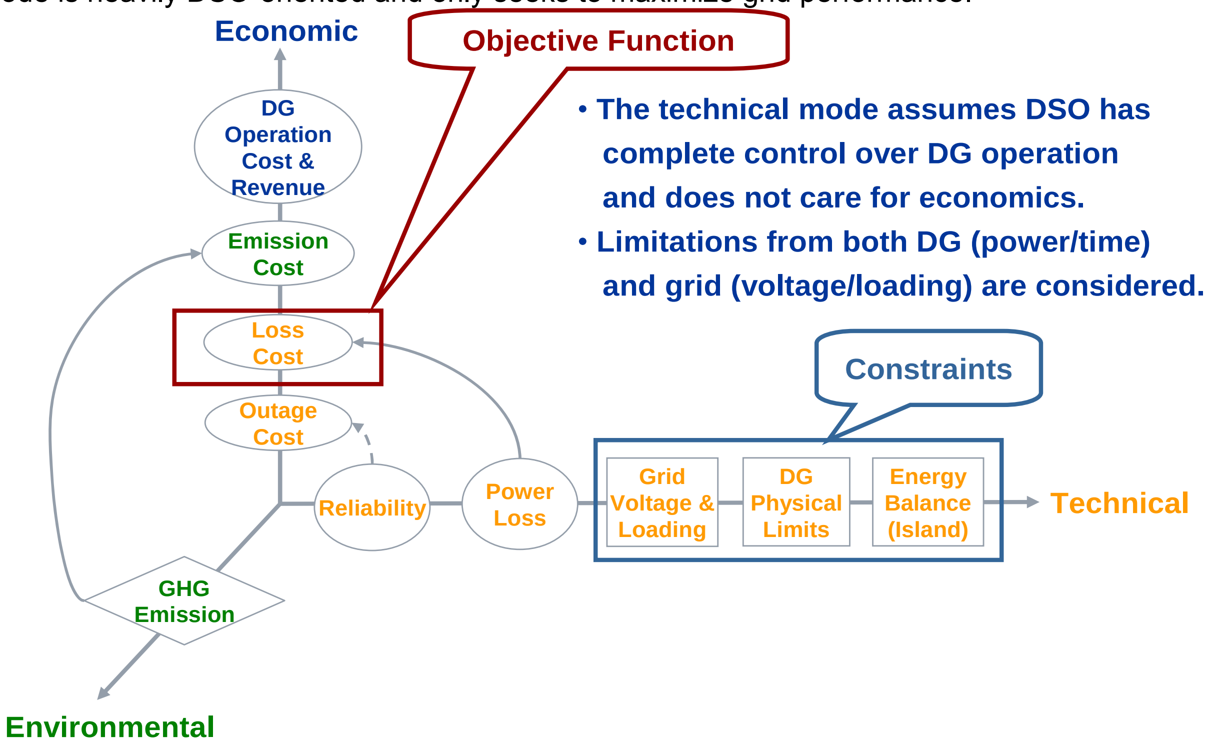

Figure 1-3 Technical Mode of Microgrid Operation

In Figure 1-4, the environmental Microgrid operation mode is graphically illustrated. This mode aims to minimize GHG emission with minimum economic and technical concerns.

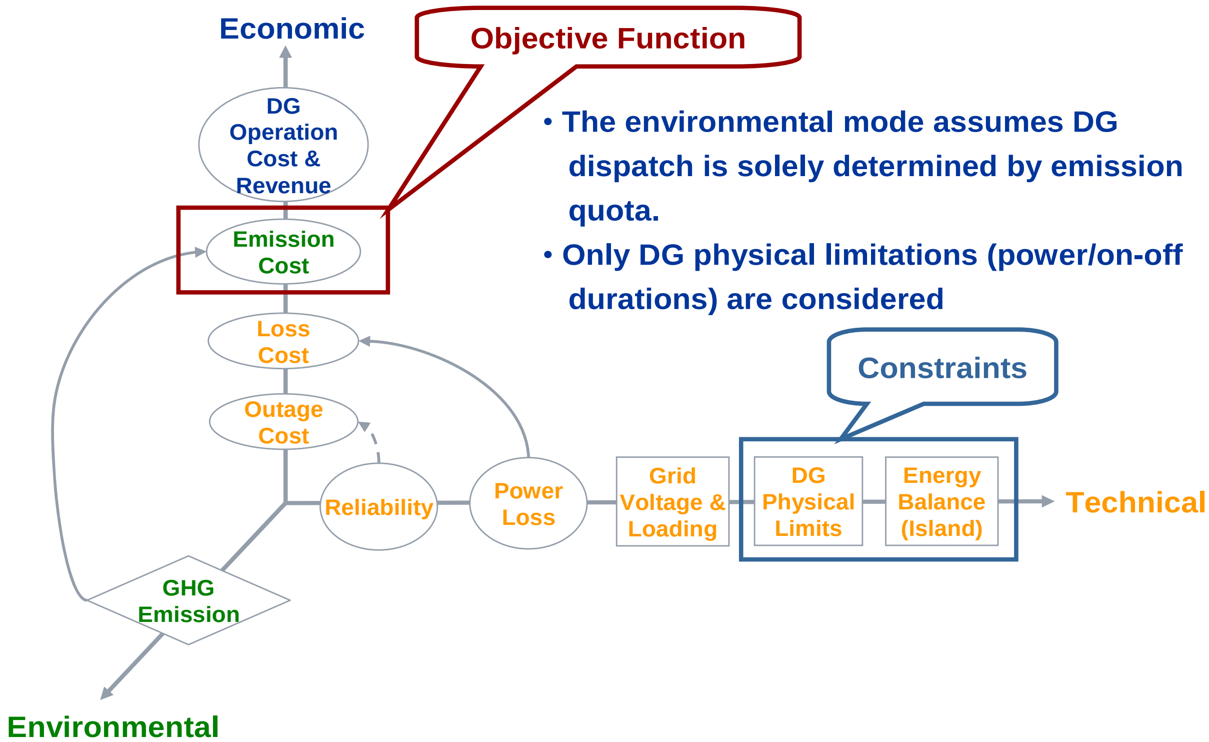

Figure 1-4 Environmental Mode of Microgrid Operation

A combined Microgrid operation mode is proposed in Figure 1-5, which can be seen as a compromise of the previous three modes with due consideration of all related aspects.

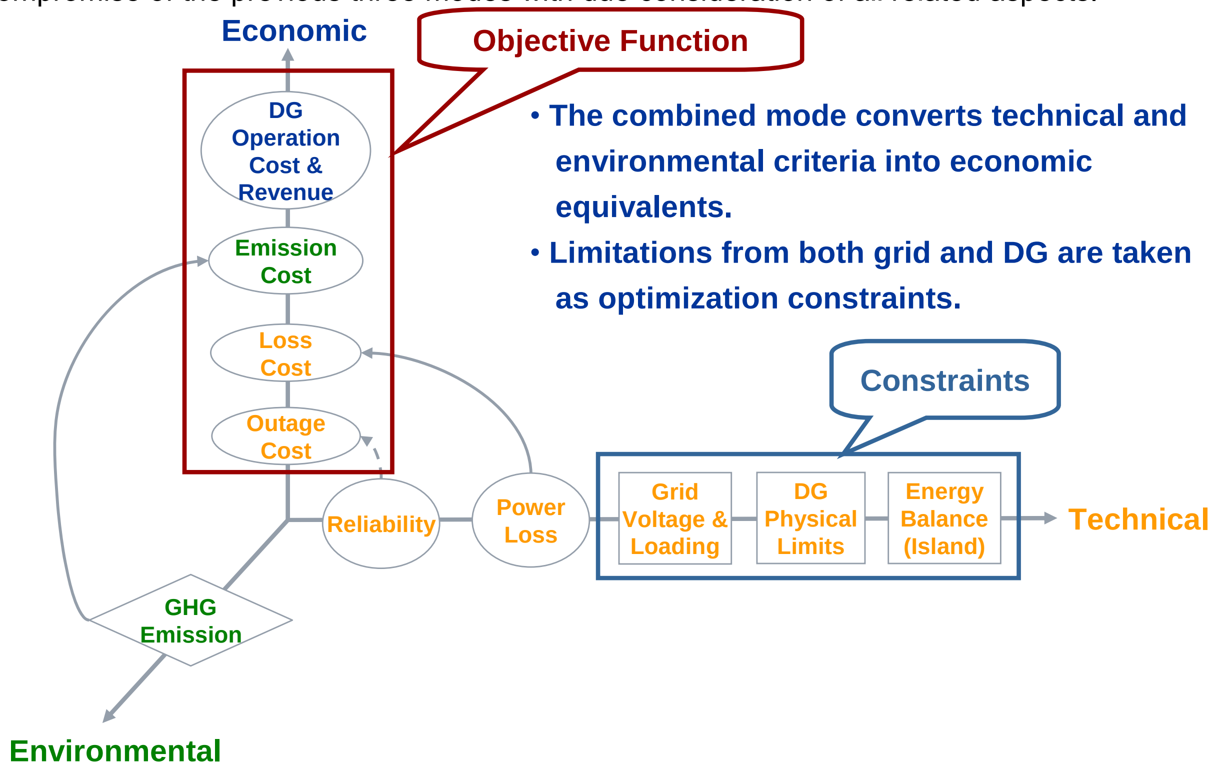

Figure 1-5 Combined Mode of Microgrid Operation

Modeling of Microgrid Components

Modeling of Micro-Generators: Controllable DG and RES Units

Micro-generators (MG) in a Microgrid can be either dispatchable distributed generator (DG) units fueled by gas or oil or intermittent renewable energy source (RES) units such as wind turbines (WT) and photovoltaics (PV). In scope of this study, the dispatchable MG units are always referred to as DG units (thus narrowing down the concept of DG herein), while all intermittent or non-dispatchable MG units are referred to as RES units. Combined heat and power (CHP) units, however, can fall into both categories depending on if it is electricity-driven (DG) or heat-driven (RES).

Technical constraints of all DG units are linearized as max/min values for active and reactive power outputs, thus operation ranges of all DG units will be simplified into rectangular shapes in a Q-P plot (i.e. apparent power limits largely ignored).

In order to facilitate mathematical modeling, the cost curves (cost to active power output) of all DG units are assumed to be continuous and quadratic so as to conform to the same QP models adopted for grid power loss.

Since DG units are viewed as fully controllable in a Microgrid, they will participate in both P- and Q-dispatches in an OPF formulation.

On the other hand, since RES active power outputs are generally intermittent and uncontrollable, they are not supposed to take part in P-dispatch at all.

There might be cases when high active power output from one or more RES unit(s) is causing grid problems that cannot be mitigated by storage or DSM measures, which forces the scheduling algorithm to switch off corresponding RES unit(s).

The reactive power outputs from RES unit, however, are subject to RES type and power electronic technology adopted for AC interface (if applicable); thus they could be potentially adjustable and listed as valid candidates for Q-dispatch procedures.

The generation cost of DG units is considered as the same quadratic model as that of traditional large thermal units. For unit i at time t, [13] [14]

$$Cst_i(t) = a_{2,i} \times P_{gen,i}^2(t) + a_{1,i} \times P_{gen,i}(t) + a_{0,i}$$

Equation 1-1

Considering the energy sold (+) to / bought from (-) the grid,

$$Rvn_i(t) = Price(t) \times P_{gen,i}(t)$$

Equation 1-2

When considering the economic behavior in periods, the switching cost, represented by $SwCst_i$ is needed and calculated by Equation 1-3,

$$SwCst_i = \sum_{t=1}^{24} S_t \times (1 - S_{t-1}) \times K_i \times \left[1 - exp(-T_{off,i,t} / T_{off\_min,i})\right]$$

Equation 1-3

For small DG units with negligible cool-off time (T_{off_min}), the switching cost is simplified as constant for each unit [31].

Therefore the economic model of single DG unit i for daily optimization can be expressed as Equation 1-4,

$$P_{DG,i} = \sum_{t=1}^{24} S_t \cdot \left[Rvn_i(t) - Cst_i(t)\right] - SwCst_i$$

Equation 1-4

For environmental estimation, pollution is taken as a cost. To evaluate the influence of GHG emission, following equation (Equation 1-5) is introduced, [11] [13]

$$EmCst_i = \sum_{t=1}^{24} S_t \cdot k_{GHG,i} \cdot P_{gen,i}(t)$$

Equation 1-5

in the Equation 1-3, Equation 1-4 and Equation 1-5, S refers to the DG switching state (1 for ON and 0 for OFF), $Price(t)$ to the power price at time t, K_i to cold start-up cost, $k_{GHG,i}$ to the emission cost per kWh generation, P_{gen} to the active power generation of DG unit.

It can be noted that economic mode of DG unit is a quadratic function, which can be solved directly by quadratic optimization.

Quadratic optimization, also called quadratic programming (QP), is a special type of mathematical optimization problem. It is the problem of optimizing (minimizing or maximizing) a quadratic function of several variables subject to linear constraints on these variables. Generally it can be formulated as following:

Assume x belongs to R^n *space. The* $n \times n$ *matrix Q is symmetric and c is any* $n \times 1$ *vector.*

Minimize: $f(x) = \frac{1}{2} x^T Q x + c^T x$

Subject to: $\begin{matrix} Ax \le b \quad \text{(inequality constraint)} \\ Ex = d \quad \text{(equality constraint)} \end{matrix}$

Because the cost function contains a constant term $a_{0,i}$, in this thesis, the QP optimization can be processed only with known switch state (S_t), whose optimization method is called unit commitment (UC) optimization and is discussed in **Fehler! Verweisquelle konnte nicht gefunden werden.**. Therefore the QP calculation, for unit i in specific time t, is developed into Equation 1-6 in this case:

Minimize: $f = S_i \times [a_{2,i} \times P_{gen}^2(i,t) + a_{1,i} \times P_{gen}(i,t) + a_{0,i}] - Price(t) \times P_{gen}(i,t)$

Subject to: $\begin{cases} P_{min}(i) \le P_{gen}(i,t) \le P_{max}(i) \\ T_{ON} \ge T_{ON,Min} \\ T_{OFF} \ge T_{OFF,Min} \end{cases}$

Equation 1-6

Modeling of Storage Units

For each storage unit, a number of technical specifications can be identified, namely:

(1) Rated energy capacity (in kWh), which corresponds to physical storage size;
(2) Peak charging / discharging power (in kW), which corresponds to the maximum amount of power that can be extracted from or injected to the storage unit within a certain period (e.g. 1 hour);
(3) Unit efficiency, which can be defined as the percent of remaining energy in a storage unit after a certain period (e.g. 1 day) of idle state.
The cost of using a storage unit can be simplified into a linear model with constant per-kWh cost for discharging (or both charging and discharging) the unit. This per-kWh cost refers to the sum of depreciated investment cost and maintenance cost.
When a single storage unit is considered only in economic terms, its operation objective under grid-connected mode can be described as maximization of profit from energy trading and can be optimized via a two-step LP procedure, while under island mode a storage unit could serve both technical (energy balance) and economic (load shifting) purposes and need to be optimized simultaneously with other DER units.

Unlike DG units, storage units have three operation states: charging, discharging and idle, which can be represented by S' as *-1*, *1* and *0*. When charging, storage unit behaves as load ($S'=-1$) and consumes power from grid. It can also behave as a generator when discharging ($S'=1$). The economic model at time t can be,

$$P_{ST}(t) = S' \times Price(t) \times P_{inst}(t)$$

Equation 1-7

According to the economical models, the operation of controllable loads and storage unit can be optimized by linear programming (LP).

Linear optimization, in mathematics, is a technique for optimization of a linear objective function, subject to linear equality and linear inequality constraints. The problem can be expressed by:

Optimize: $f(x) = c^T x$

Subject to: $Ax \le b$

In order to facilitate mathematical modeling, the initial charge state for every day is set to 50%. Considering storage efficiency and the maximum capacity for the storage, the LP formulation can be expressed as Equation 1-8:[34]

Maximize: $f = \sum_{t=1}^{24} P_{ST}(t)$

Subject to: $\begin{cases} P_{min} \le P_{inst}(t) \le P_{max} \\ \sum_{t=1}^{24} P_{inst}(t) = 24 \times HrLoss \\ 0 \le E(t) \le E_{\max} \end{cases}$

Equation 1-8

In Equation 1-8, $E(t)$ is the stored energy at time t, it can be calculated by Equation 1-9:

$E(t) = E(t-1) - P_{inst}(t) - HrLoss$ with $E(0) = 50\% \times E_{max}$

Equation 1-9

where E_{max} refers to the capacity of storage unit, $HrLoss$ to the natural energy loss per hour (also called storage efficiency), and P_{inst} is the instant power consuming or generation at time t.

Modeling of Demand Side Management (DSM) on Loads

Two basic models of DSM measures can be considered for Microgrid scheduling task: interruptible loads and transferrable loads.

The former load type assumes its power consumption to be instantaneous and does not retrace the not-supplied energy later in the day after DSM controller chooses to cut its supply for a certain period—an example can be the lightning of non-critical locations.

The latter load type, when defined under a Microgrid scheduling framework, always assumes its total energy consumption in a day to be constant and the DSM procedure applied to it can be largely seen as an equivalent load-shifting maneuver—water pumps can be taken as a good sample of this case.

Associated costs for the former load type are obviously larger than the later, while for both cases choice of if and how DSM measure should be applied depends on comparison of execution cost and corresponding benefit that could be identified for each potential DSM scenario. Integration of DSM models into the large optimization framework of Microgrid scheduling follows a similar approach as that of storage units.

Like storage units, the cost of DSM can be modeled as Equation 1-10,

$$Cst_{Load} = Price(t) \times P_{load}(t)$$

Equation 1-10

For controllable load, total daily energy consumption should be maintained so as to minimize economic and social aftermaths. Therefore one of the constraints should be the balance of energy consuming. The LP formulation for daily DSM modification can be described as Equation 1-11:

Minimize: $$f = \sum_{t=1}^{24} [Price(t) \times P'_{load}(t)]$$

Subject to: $$\begin{cases} 0 \le P'_{load}(t) \le P_{load,max} \\ \sum_{t=1}^{24} P'_{load}(t) = \sum_{t=1}^{24} P_{load}(t) \end{cases}$$

Equation 1-11

Simplified Network Model Based on NtL Load Flow Method

Refer to NtL Load Flow documentation.

During the optimization of DG scheduling, there are constraints concerning with the network operation, such as loading and voltage. Additionally, power loss needs to be minimized for technical evaluation. It is quite necessary to determine the transfer function between

Microsource generation and network performance. In this part, a set of formulary for fast estimation is developed under certain approximations. Detailed mathematic transformation is not explained in this thesis. [43]; [44]

1. Loading Ratio

Linearized formulas are expressed in Equation 1-12, here $CofA, CofB, CofC \text{ and } CofD$ are elements in coefficient matrix.

$$\begin{cases} P_{lk} = CofA \cdot P_{Nd} + CofB \cdot Q_{Nd} + CofC \\ Q_{lk} = CofA \cdot P_{Nd} + CofB \cdot Q_{Nd} + CofC \end{cases} \quad \text{and} \quad I_{rat} = \frac{\sqrt{P_{lk}^2 + Q_{lk}^2}}{100 \cdot CofD}$$

Equation 1-12

According to the network parameter, a coefficient matrix ($CofRat_{(2CntNd+1)\times 2CntLk}$) as shown in Figure 1-6 is created for P_{lk}, Q_{lk} & I_{rat} calculation

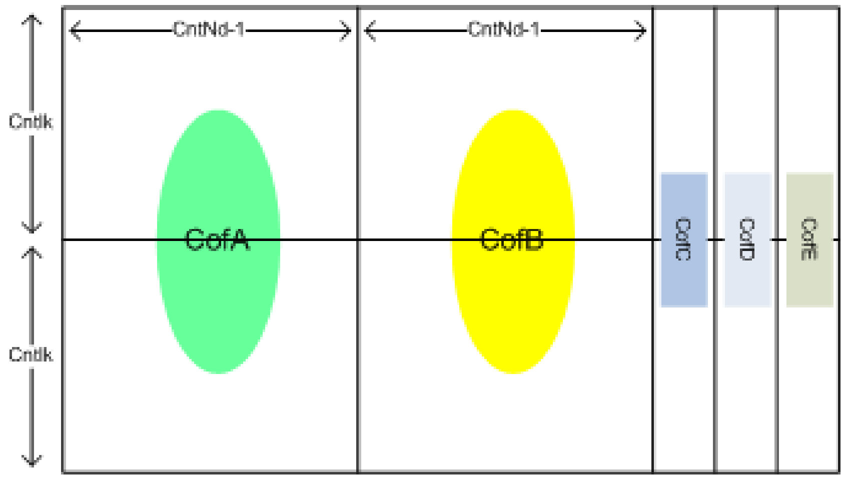

Figure 1-6 Coefficient Matrix for Loading Calculation

2. Voltage

Linearized formula is expressed in **Equation 1-13**.

$$U_{node} = VtA \cdot P_{Nd} + VtB \cdot Q_{Nd} + VtC$$

Equation 1-13

According to the network parameter, a coefficient matrix ($CofVlt_{(2CntNd-1)\times(CntNd-1)}$) shown in Figure 1-7 is created.

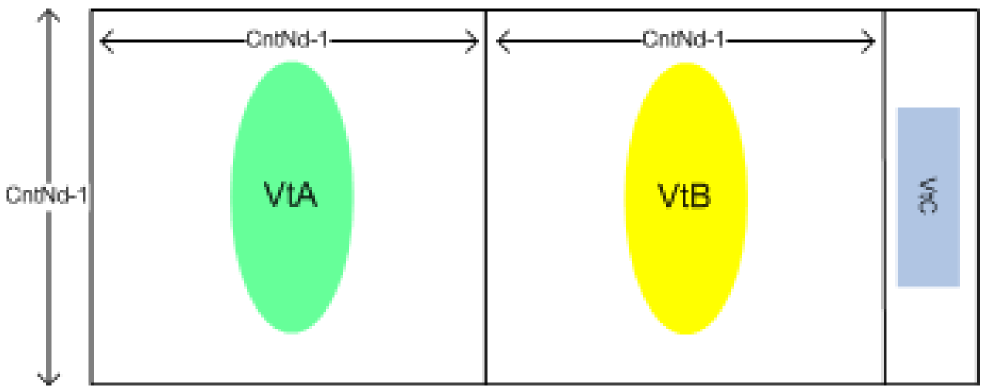

Figure 1-7 Coefficient Matrix for Voltage Calculation

3. Power Loss

For technical mode, minimum total power loss, which can be achieved by optimal power flow (OPF), becomes objective function. In power flow calculation, the fast calculation of active and reactive power loss can be processed by **Equation 1-15**

$$\begin{cases} dP = R \cdot \dfrac{S^2}{U^2} \\ dQ = X \cdot \dfrac{S^2}{U^2} \end{cases} \quad \& \quad \begin{cases} S^2 = P_{lk}^2 + Q_{lk}^2 \\ P_{lk} = \vec{\alpha}_P \cdot \vec{P}_{Nd} + \vec{\beta}_P \cdot \vec{Q}_{Nd} + \gamma_P \\ Q_{lk} = \vec{\alpha}_Q \cdot \vec{P}_{Nd} + \vec{\beta}_Q \cdot \vec{Q}_{Nd} + \gamma_Q \end{cases}$$

Equation 1-14

$$[P_{loss,1} \cdots P_{loss,n} \mid Q_{loss,1} \cdots Q_{loss,n}]^T = \vec{x}^T \cdot \vec{L}_{S2} \cdot \vec{x} + \vec{L}_{S1} \cdot \vec{x} + L_{S0}$$

Equation 1-15

with $\vec{x} = [P_1 \cdots P_n \mid Q_1 \cdots Q_n]^T$

$\vec{L}_{S2}$ is the coefficient matrix, whose $2n \times 2n$ elements are the coefficients of the quadratic term. Consider it more detailed, in a link element, equation for active power loss is **Equation 1-16**.

$$\begin{aligned} dP &= \frac{R}{2}\left[(\frac{S_i}{U_i})^2 + (\frac{S_o}{U_o})^2 \right] \\ &= \frac{R}{2} \cdot \frac{[P_{lk}^2 + Q_{lk}^2 + P_{lk}^2 + Q_{lk}^2] + dP^2 + dQ^2 - 2 \cdot dP \cdot P_{lk} - 2 \cdot dQ \cdot Q_{lk}}{U_N^2} \\ &= R \cdot \frac{P_{lk}^2 + Q_{lk}^2}{U_N^2} - R \cdot \frac{dP}{U_N^2} \cdot P_{lk} - R \cdot \frac{dQ}{U_N^2} \cdot Q_{lk} + \frac{R \cdot \left[dP^2 + dQ^2\right]}{2 \cdot U_N^2} \\ &= \alpha \cdot (P_{lk}^2 + Q_{lk}^2) - \beta_P \cdot P_{lk} - \beta_Q \cdot Q_{lk} + \gamma \end{aligned}$$

Equation 1-16

With assuming: $\alpha = \dfrac{R}{U_N^2}; \beta_P = R \cdot \dfrac{dP}{U_N^2}; \beta_Q = R \cdot \dfrac{dQ}{U_N^2}; \gamma = \dfrac{R \cdot [dP^2 + dQ^2]}{2 \cdot U_N^2}$

Let $\begin{bmatrix} P_{lk} \\ Q_{lk} \end{bmatrix} = \begin{bmatrix} a' & 0 \\ 0 & c' \end{bmatrix} \cdot \begin{bmatrix} P_{nd} \\ Q_{nd} \end{bmatrix} + \begin{bmatrix} b \\ d \end{bmatrix} = \begin{bmatrix} a \\ c \end{bmatrix} \cdot x + \begin{bmatrix} b \\ d \end{bmatrix}$. So only node information is considered in the calculation, the above equation can be evaluated into **Equation 1-17**

$$\begin{aligned} dP &= \alpha \cdot [(ax+b)^2 + (cx+d)^2] - \beta_P \cdot (ax+b) - \beta_Q \cdot (cx+d) + \gamma \\ &= \alpha \cdot (a^2 + c^2) \cdot x^2 + 2 \cdot \alpha \cdot (ab + cd - \beta_P \cdot a - \beta_Q \cdot c) \cdot x \\ &\quad + [\alpha \cdot (b^2 + d^2) + \beta_P \cdot b + \beta_Q \cdot d + \gamma] \\ &= A \cdot x^2 + B \cdot x + C \end{aligned}$$

With $\begin{cases} A = \alpha \cdot (a^2 + c^2) \\ B = 2 \cdot \alpha \cdot (ab + cd - \beta_P \cdot a - \beta_Q \cdot c) \\ C = \alpha \cdot (b^2 + d^2) + \beta_P \cdot b + \beta_Q \cdot d + \gamma \end{cases}$

Equation 1-17

Microgrid Scheduling as an Optimization Process

Definition of the Objective Function

In section Chapter 0, four operation modes have been proposed for the Microgrid scheduling task. For each one of them, a different objective function has been adopted. In this section, more detailed mathematical models will be provided.
In real-life applications, the scheduling task of a Microgrid is performed by a Microgrid central controller (MGCC). The MGCC unit can be adopted for both vertically integrated (non-liberalized) and unbundled (liberalized) market models, as shown by Figure 1-8 and Figure 1-9. It can be seen that cash flows in the integrated Microgrid model prove to be much simpler than unbundled market condition due to its unified ownership definition.
The role of MGCC in the integrated market model can be viewed as the central executer that arbitrarily makes dispatch decisions for all MG and storage units; while the MGCC in an unbundled market model serves as a coordinator rather than a controller, which collects and distributes economic and technical information from and to all MG / storage operators and let each operator make its own dispatch decision. Conspicuously, the integrated market model adopts centralized control while the unbundled market model adopts decentralized control.

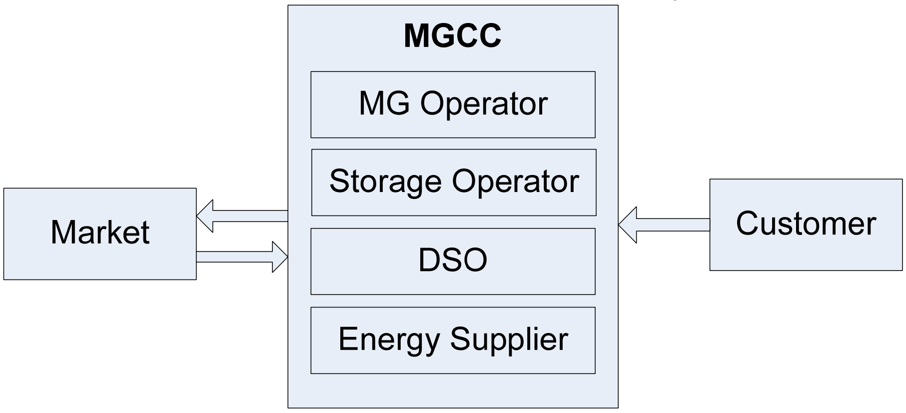

Figure 1-8 Cash Flow in Integrated Microgrid Market Model

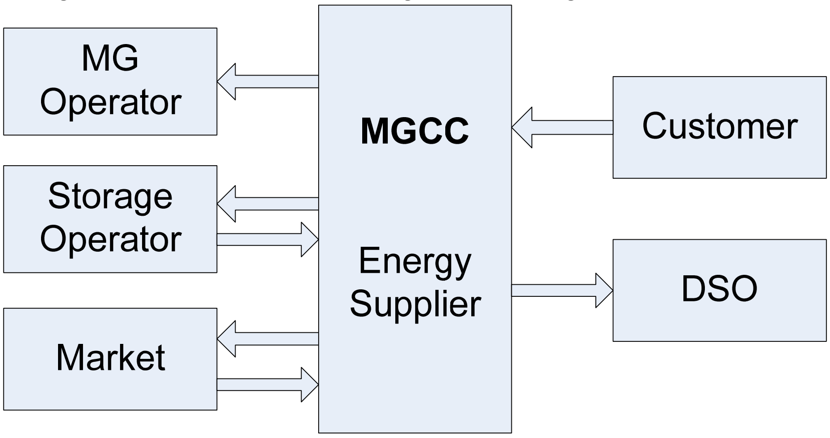

Figure 1-9 Cash Flow in Unbundled Microgrid Market Model

Despite ownership and operational differences, the integrated and unbundled Microgrid models could arrive at different scheduling decisions given the same physical setup and same market conditions. Thus

can be expressed as maximization of the total profits in terms of combination of individual cost/revenue entries:

$Maximize\ G = r_{trade} - \left(f_{energy} + f_{switch} + f_{loss} + f_{emission} \right)$ for grid-connected configuration

Or

$Minimize\ F = f_{energy} + f_{switch} + f_{loss} + f_{emission}$ for islanded configuration

with

r_{trade} as revenue/cost from sell/buy electricity in market,
f_{energy} as total generation cost of DG,
f_{switch} as switching cost of DG operation,
f_{loss} as total energy loss cost in the grid, and
femission as total emission cost from electricity generation.

The cost entries in (1) are calculated on the basis of the on/off status and active power outputs of DG units:

$$r_{trade} = q_t \cdot M_t \quad (M_t > 0\ then\ r_{trade}\ as\ revenue)$$

$$f_{energy} = \sum_t \sum_n S_t \cdot \left(a_n \cdot P_{n,t}{}^2 + b_n \cdot P_{n,t} + c_n \right)$$

$$f_{switch} = \sum_t \sum_n S_t \cdot (1 - S_{t-1}) \cdot K_n \cdot \left[1 - \exp(-T_{off,n,t} / T_{off\_\min,n}) \right]$$

$$f_{emission} = \sum_t \sum_n S_t \cdot k_{GHG,n} \cdot P_{n,t}$$

where t refers to the specific hour, n to the DG unit, S to the specific DG switching state (0/1), qt to the market electricity price, Mt to the sold (+) / bought (-) electricity to / from the grid, Kn to cold start-up cost, kGHG to emission cost per kWh generation, and P to active power output from DG. For small DG units with negligible cool-off time (Toff_min), the switching cost (fswitch) can be seen as constant and thus independent from switched-off duration (Toff).

Definition of Optimization Constraints

Three sets of system operational constraints are identified.

$$1.\ Energy\,Balance: \begin{cases} \Sigma P_{Gen} - \Sigma P_{Load} \pm \Sigma P_{trade} - \Sigma P_{Loss} = 0 \\ \Sigma Q_{Gen} - \Sigma Q_{Load} \pm \Sigma Q_{trade} - \Sigma Q_{Loss} = 0 \end{cases}$$

$$2.\ DG\ Physical\,Limit:$$

$$\begin{cases} Min\,on/off\ \ duration: & \begin{cases} T_{on} \geq T_{on\_\min} \\ T_{off} \geq T_{off\_\min} \end{cases} \\ Max/Min\,Output: & P_{\min} \leq P \leq P_{\max}, \quad Q_{\min} \leq Q \leq Q_{\max} \end{cases}$$

$$3.\ Grid\ Technical\,Limit:$$

$$\begin{cases} Voltage\,Band: & U_{\min} \leq U \leq U_{\max} \\ Device\,Loading: & I \leq I_{thermal} \end{cases}$$

Linearised load flow based on node-to-link deduction is performed to obtain real-number estimation matrices that could be used for approximating modulus of complex variables in both objective function and constraints of an optimal power flow procedure, more specifically:

$$\vec{u} \cong \vec{B}_u \cdot \vec{x} + \vec{C}_u$$
$$\vec{i} \cong \sqrt{\left(\vec{B}_{ip} \cdot \vec{x} + \vec{C}_{ip}\right)^2 + \left(\vec{B}_{iq} \cdot \vec{x} + \vec{C}_{iq}\right)^2}$$
$$f_{loss} = l \cong \vec{x}^T \cdot \vec{A}_l \cdot \vec{x} + \vec{B}_l \cdot \vec{x} + \vec{C}_l$$
$$with$$
$$\vec{x} = \left[P_1, \cdots P_N, Q_1, \cdots Q_N\right]^T, \quad \vec{u} = \left[U_1, \cdots U_N\right]^T,$$
$$\vec{i} = \left[I_1, \cdots I_M\right]^T, \quad l = \sum_M P_{loss}$$

Microgrid Scheduling in Coupled and Decoupled Formulations

Detailed Definition of Microgrid Operation Modes

Based on the above models, four modes mentioned in **Fehler! Verweisquelle konnte nicht gefunden werden.** can be achieved. All equations, from Equation 1-12 to Equation 1-11 will not be explained in detail.

1. *Economic Mode*

   In this mode, considering *n* DG units, the maximum profit of DG generation is pursued and only constraint of DG unit itself is considered. Therefore equation for optimization can be expressed as **Equation 1-18**,

Minimize: $$f_{DG} = \sum_{i=1}^{n} (\sum_{t=1}^{24} S_t \cdot [Cst_i(t) - Rvn_i(t)] + SwCst_i)$$

Subject to: $$\begin{cases} P_{min,i} \le P_{gen,i}(t) \le P_{max,i} \\ T_{ON,i} \ge T_{ON,i,Min} \\ T_{OFF,i} \ge T_{OFF,i,Min} \end{cases} \quad \textit{with} \quad i \in (1, CntDG)$$

Equation 1-18

In which, equations for $Cst_i(t)$, $Rvn_i(t)$ and $SwCst_i(t)$ have been discussed in **Fehler! Verweisquelle konnte nicht gefunden werden.**, $CntDG$ is the number of DG units, $T_{ON,Min}$ and $T_{OFF,Min}$ is the minimum ON or OFF duration of units.

2. *Technical Mode*

   In this mode, optimal power flow calculation, which leads to minimum active power loss, is executed; constraints both for network operation and DG operation are taken into account (**Equation 1-19**).

Minimize: $$f_{Loss} = \vec{x}^T \cdot \vec{L}_{S2} \cdot \vec{x} + \vec{L}_{S1} \cdot \vec{x} + L_{S0}$$

Subject to:
$$\begin{cases} U_{min} \le [U_{node,1} \cdots U_{node,n}] \le U_{max} \\ [I_{rat,1} \cdots I_{rat,m}] \le I_{thermal} \\ P_{min,i} \le P_{gen,i}(t) \le P_{max,i} \\ T_{ON,i} \ge T_{ON,i,Min} \\ T_{OFF,i} \ge T_{OFF,i,Min} \end{cases} \quad \textit{with} \quad \begin{cases} i \in (1, CntDG) \\ n \in (1, CntNd) \\ m \in (1, CntLk) \\ \vec{x} = [P_1 \cdots P_n \mid Q_1 \cdots Q_n]^T \end{cases}$$

Equation 1-19

In which, $CntDG$ is the number of DG units, $CntNd$ is the number of node elements and $CntLk$ is the number of link elements.

3. *Environmental Mode*

In this mode, the GHG emission of Microgrid is regulated strictly (**Equation 1-20**),

Minimize: $$f_{Emission} = \sum_{i=1}^{CntDG} EmCst_i + k'_{GHG} \cdot P_{Import}$$

Subject to:
$$\begin{cases} P_{min,i} \le P_{gen,i}(t) \le P_{max,i} \\ T_{ON,i} \ge T_{ON,i,Min} \\ T_{OFF,i} \ge T_{OFF,i,Min} \end{cases} \quad \textit{with} \quad i \in (1, CntDG)$$

Equation 1-20

In which, k'_{GHG} refers to external GHG emission cost, P_{Import} to the purchased power from MV network, $CntDG$ to the number of DG units.

4. *Combined Mode*

In this mode, all the objectives and constraints are needed. Therefore the equation shows like **Equation 1-21**:

Minimize: $$f = f_{DG} + k_{Loss} \cdot f_{Loss} + f_{Emission}$$

Subject to:
$$\begin{cases} U_{min} \le [U_{node,1} \cdots U_{node,n}] \le U_{max} \\ [I_{rat,1} \cdots I_{rat,m}] \le I_{thermal} \\ P_{min,i} \le P_{gen,i}(t) \le P_{max,i} \\ T_{ON,i} \ge T_{ON,i,Min} \\ T_{OFF,i} \ge T_{OFF,i,Min} \end{cases} \quad \textit{with} \quad \begin{cases} i \in (1, CntDG) \\ n \in (1, CntNd) \\ m \in (1, CntLk) \\ \vec{x} = [P_1 \cdots P_n \mid Q_1 \cdots Q_n]^T \end{cases}$$

Equation 1-21

Here k_{Loss} refers to the loss cost for DSO.

Solution Techniques for the Microgrid Scheduling Task

Standard QP Sub-Routines: OPF and DG Dispatch

Quadratic optimization, also called quadratic programming (QP), is a special type of mathematical optimization problem. It is the problem of optimizing (minimizing or maximizing) a quadratic function of several variables subject to linear constraints on these variables. Generally it can be formulated as following:

Assume *x* belongs to R^n space. The $n \times n$ matrix Q is symmetric and c is any $n \times 1$ vector.

Minimize: $f(x) = \frac{1}{2} x^T Q x + c^T x$

Subject to: $$\begin{aligned} &Ax \le b \quad \text{(inequality constraint)} \\ &Ex = d \quad \text{(equality constraint)} \end{aligned}$$

Specified in this thesis, the OP calculation can be processed only with the known On/Off state, because the cost function contains a constant term $a_{0,i}$. Therefore the QP calculation, for a single unit, is developed in this case:

Minimize: $$f(x) = SwSt(i,t) \times [a_{2,i} \times P_{gen}^2(i,t) + a_{1,i} \times P_{gen}(i,t) + a_{0,i}] - Price(t) \times P_{gen}(i,t)$$

Subject to:

$$P_{min}(i) \le P_{gen}(i,t) \le P_{max}(i)$$

When considering n DG units in the distribution network, network operation constraints should be counted in. Then the formula can be developed in Equation X.

Minimize:

$$f(x) = \sum_{i=1}^{n} \left\{ SwSt(i,t) \times [a_{2,i} \times P_{gen}^2(i,t) + a_{1,i} \times P_{gen}(i,t) + a_{0,i}] - Price(t) \times P_{gen}(i,t) \right\}$$

Subject to:

$$\begin{cases} U_{min} \le U(P_{gen}(i_1,t), P_{gen}(i_2,t), \cdots P_{gen}(i_n,t)) \le U_{max} \\ I_{loading}(P_{gen}(i_1,t), P_{gen}(i_2,t), \cdots P_{gen}(i_n,t)) \le I_{thermal} \\ P_{min}(i) \le P_{gen}(i,t) \le P_{max}(i) \end{cases}$$

With the known $SwSt_{1 \times n}$, it can be transformed into the general QP form as following, in which L_{S2} and L_{S1} are created by $a_{2,i}$ and $a_{1,i} - Price(t)$.

Minimize: $f(x) = \frac{1}{2} \cdot P_{gen}^T \cdot L_{S2} \cdot P_{gen} + L_{S1} \cdot P_{gen}$

Subject to: $$\begin{cases} U_{min} \le U(P_{gen}(i_1,t), P_{gen}(i_2,t), \cdots P_{gen}(i_n,t)) \le U_{max} \\ I_{loading}(P_{gen}(i_1,t), P_{gen}(i_2,t), \cdots P_{gen}(i_n,t)) \le I_{thermal} \\ P_{min}(i) \le P_{gen}(i,t) \le P_{max}(i) \end{cases}$$

Standard LP Sub-Routines: Daily Storage and DSM Planning

Linear optimization, in mathematics, is a technique for optimization of a linear objective function, subject to linear equality and linear inequality constraints. The problem can be expressed by:

Optimize: $f(x) = c^T x$

Subject to: $Ax \le b$

According to the economical models, the operation of controllable loads and storage unit can be optimized by linear programming (LP).

For controllable load, the daily energy consuming should be maintained for the purpose of social harmony. Therefore one of the constraints should be the balance of consuming. The formulary for daily modification can be described as:

Minimize: $$f(t) = \sum_{t=1}^{24} [Price(t) \times P'_{load}(t)]$$

Subject to: $$\begin{cases} 0 \le P'_{load}(t) \le P_{load,max} \\ \sum_{t=1}^{24} P'_{load}(t) = \sum_{t=1}^{24} P_{load}(t) \end{cases}$$

Unlike DG units, the operation state (charging, discharging or none) of storage unit can be concluded by the result of LP calculation. For the service life of storage unit and the convenient usage, the initial charge state for every day is set to 50%. Considering the natural loss of energy and the maximum capacity for the storage, the formula can be expressed as:

Maximize: $$f(t) = \sum_{t=1}^{24} [Price(t) \times P_{inst}(t)]$$

Subject to: $$\begin{cases} P_{min} \le P_{inst}(t) \le P_{max} \\ \sum_{t=1}^{24} P_{inst}(t) = TotalLoss \\ 0 \le E(t) \le E_{max} \\ U_{min} \le U(P_{gen}(i_1,t), P_{gen}(i_2,t), \cdots P_{gen}(i_n,t)) \le U_{max} \\ I_{loading}(P_{gen}(i_1,t), P_{gen}(i_2,t), \cdots P_{gen}(i_n,t)) \le I_{thermal} \\ P_{min}(i) \le P_{gen}(i,t) \le P_{max}(i) \end{cases}$$

In the above equation, $E(t)$ is the instant energy at time t, it can be calculated by:

$$E(t) = E(t-1) - P_{inst}(t) - HrLoss \qquad \text{with} \qquad E(0) = 50\% \times E_{max}$$

Genetic Algorithm (GA) Solution to the Scheduling Task

Among all the methods introduced in chapter **Fehler! Verweisquelle konnte nicht gefunden werden.**, application of Genetic Algorithm (GA) in research of Microgrid is mainly studied in this section as one of heuristic algorithms. Aside from basic idea and general procedure of GA, subvariations and formulations specific to Microgrid scheduling task are introduced. Finally, the disadvantage of GA found in this research is explained.

GA is a search technique for finding viable solutions to optimization and search problems. It is a class of evolutionary algorithms, categorized as global search heuristics. Individuals with different genes are created. The performance of various individuals can be calculated by the objective functions and expressed by fitness. Fitness comparison and development is the basic motivation for evolution. Gene with better fitness is reserved and spread generation by generation.

To ensure the convergence of solutions and avoid local optimization, penalty method is introduced into genetic algorithm. This method replaces a constraint optimization by a series of unconstrained problems. When relaxation of the constraints is necessary to arrive at a convergent solution, penalty function works and penalty factors [21] are added to the fitness. In this research penalty function is defined as Equation 1-22,

$$Pen = p \cdot Gen^{R}$$

Equation 1-22

In Equation 1-22, Gen is the generation number, p and R are constants, which have great influence on the convergence of calculation. Improper p and R may lead to convergence failure. In this research, three sets of penalty factors are introduced, representing

1. Dissatisfaction of network operation limit (voltage or loading) $\Rightarrow p_1; R_1$

2. Power imbalance $\Rightarrow p_2; R_2$

3. Violation of DG operation criterion $\Rightarrow p_3; R_3$

Due to structure difference, the influence of p and R varies from network to network. Therefore all three groups of p and R need to be updated when the objective Microgrid is changed. Power imbalance is only considered in the case of electrical island, which is a prospective topic in future and not discussed in this thesis. Therefore influence of p_2 and R_2 is neglected when Microgrid is interconnected to MV grid. Different values for p_1, R_1, p_3 and R_3 should be examined before every optimization. For testing network shown in Figure 1-24, 12 groups of p and R are listed in Table 1-2. From the results shown in Figure 1-10, it can be concluded that for this network, *Group 11* shows the best convergence for GA method.

With sufficient evolutions, all penalties should (but not always) become zero because all constraints should be satisfied finally. Thus in general, after a certain number of generations the solution to optimization problem should be found under a good set of parameter configuration.

	p_1	R_1	p_2	R_2	p_3	R_3
Group 1	1000	0.8	100	0.8	1000	0.5

Group 2	1000	0.8	100	0.8	1000	0.8
Group 3	2000	0.8	100	0.8	1000	0.5
Group 4	2000	0.8	100	0.8	2000	0.8
Group 5	2000	0.8	100	0.8	3000	0.8
Group 6	3000	0.5	100	0.8	2000	0.8
Group 7	3000	0.6	100	0.8	2000	0.8
Group 8	3000	0.7	100	0.8	2000	0.8
Group 9	3000	0.8	100	0.8	1000	0.5
Group 10	3000	0.8	100	0.8	2000	0.5
Group 11	3000	0.8	100	0.8	2000	0.6
Group 12	3000	0.8	100	0.8	2000	0.7

Table 1-2 Configurations for Testing the Convergence

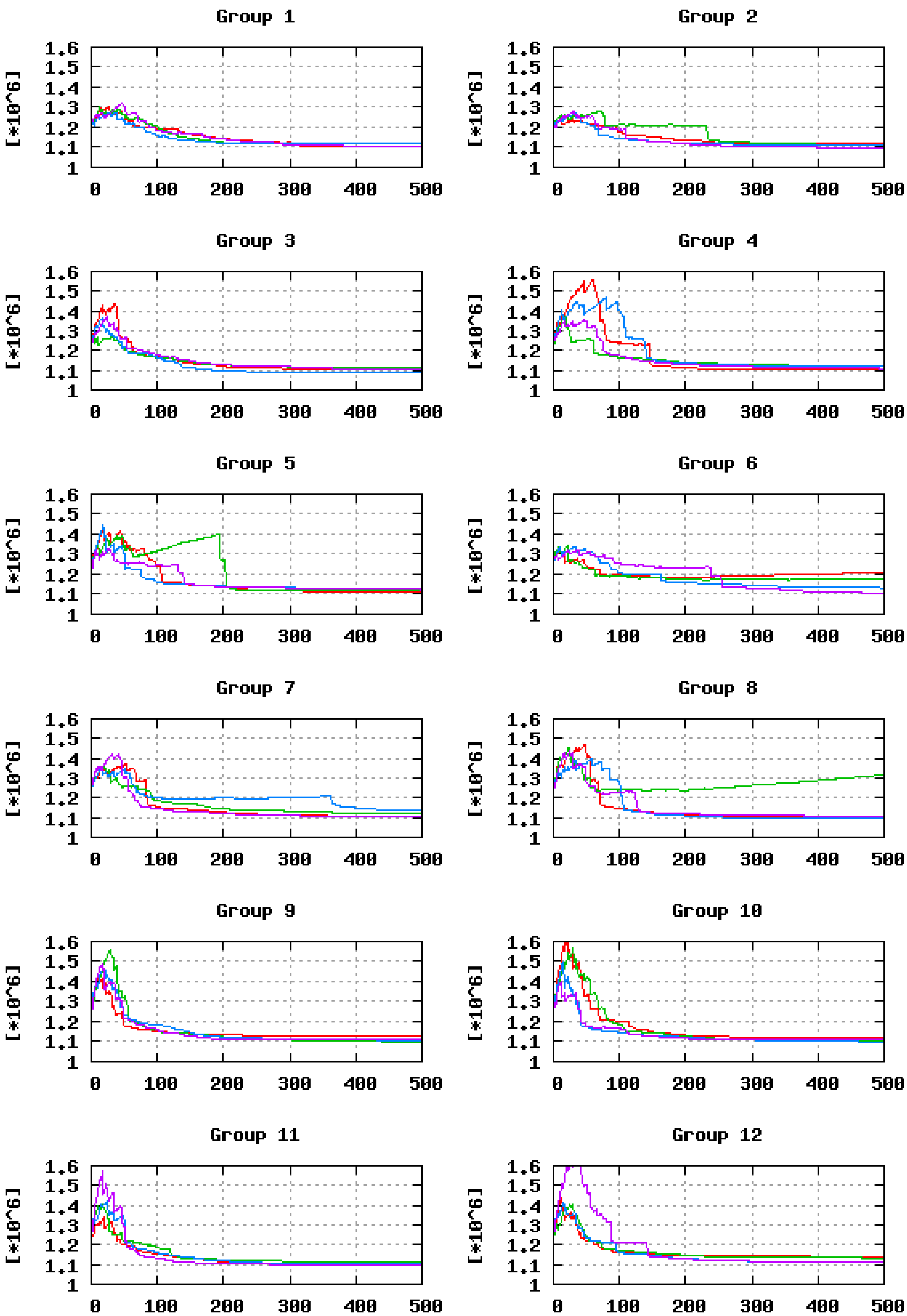

Figure 1-10 Testing Results

Initialization

In this research, gene of GA refers to the unit commitment schedule of DG units and fitness is the evaluated performance under different genes. Firstly a matrix with $CntDG \times 24$ elements is created randomly, in which $CntDG$ refers to DG number in Microgrid. This matrix represents the ON/OFF scheduling of DGs in 24 hours. Its elements are 0 (DG OFF) or 1 (DG ON). Certain values for minimum ON/OFF duration of DG units are preferred due to both technical and economic considerations. Normally with higher DG capacity, the minimum ON/OFF durations become larger in response. For creation of the scheduling matrix, this duration constraint should be considered and satisfied.

Theoretically in GA, each generation will be composed of a certain number of individuals; and for the UC problem, each individual will correspond to a certain DG scheduling matrix. After repeatedly creating the switch-state-matrix for *n* times, a set of individuals is generated and *n* is called the population size of this generation. Increased population means increased variety of genes, which will increase the speed of finding the solution.

Evolution

After the creation of the initial generation, calculations for optimization problems are processed for each individual, whose methods are introduced in **Fehler! Verweisquelle konnte nicht gefunden werden.**. To estimate these *n* individuals, fitness calculation is introduced and the results are recorded for further comparison. According to adopted operation modes, the objective function can be defined as: [3]

1. *Economic Mode*

$$\begin{cases} Fit_{Eco} = Cost_{generation} + Cost_{switching} + Trade_{power} \\ Fit_{total,1} = Fit_{Eco} + Penalty_{power} + Penalty_{unit} \end{cases}$$

Equation 1-23

2. *Technical Mode*

$$\begin{cases} Fit_{Tech} = Cost_{power\,loss} \\ Fit_{total,2} = Fit_{Tech} + Penalty_{power} + Penalty_{unit} + Penalty_{network} \end{cases}$$

Equation 1-24

3. *Environmental Mode*

$$\begin{cases} Fit_{Env} = Cost_{emission} \\ Fit_{total,3} = Fit_{Env} + Penalty_{power} + Penalty_{unit} \end{cases}$$

Equation 1-25

4. *Combined Mode*

$$Fit_{total,4} = Fit_{Eco} + Fit_{Tech} + Fit_{Env} + Penalty_{power} + Penalty_{unit} + Penalty_{network}$$

Equation 1-26

Here $Penalty_{power}$ represents the penalty of power imbalance. $Penalty_{unit}$ refers to the violation of ON/OFF duration limit and $Penalty_{network}$ to the dissatisfaction of network constraints, including overloading or voltage failure.

After the fitness calculation, individuals are ordered by total fitness. Among them, some with best fitness are taken as elite individuals. Similar to nature evolution, some individuals are eliminated in the evolutionary process. In the mean time, in order to keep the diversity of gene, new individuals should be introduced. [24]

Besides newly introduced individuals, the existing individuals are evolved by crossover of their genes, shown in Figure 1-11. The colored parts are defined as exchangeable genes. As the evolution continues, the individuals with similar "gene" will increase, which increase the possibility of local optimization. [24] [25]

Mutation, as show in Figure 1-12 is applied to avoid local optimization. Mutation prevents the genes of individuals from becoming too similar to each other. Monotonic genes will slow or even stop evolution, which leads to a high risk of arriving at a local optimization. In application, plenty of individuals with same gene do exist. To increase the algorithm efficiency, optimization results of calculated individuals are stored. When individual with old gene appears, the result can be acquired directly from the storage, because same gene always leads to the same optimization result. [25]

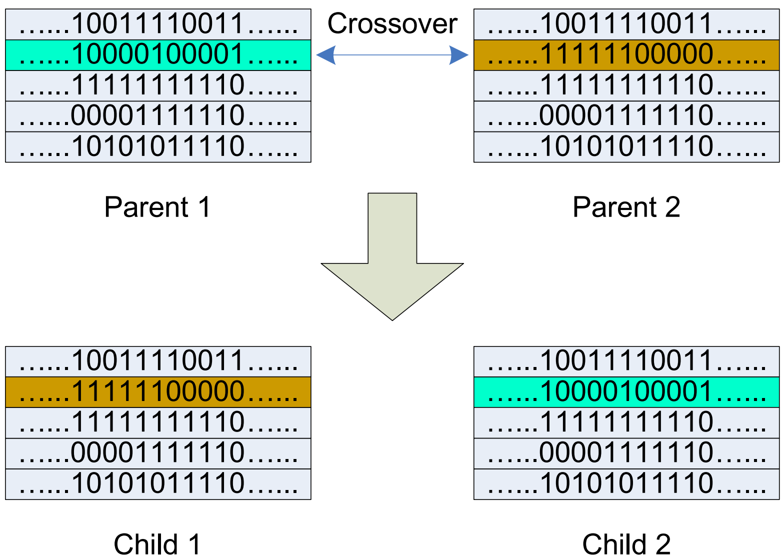

Figure 1-11 Crossover between Individuals

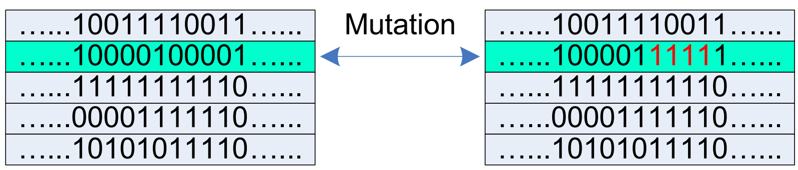

Figure 1-12 Mutation of Individual

When the new generation is created, it should be estimated by optimization and Fitness Calculation. And individuals with bad fitness are eliminated and new individuals are introduced again. This process shown in Figure 1-13 is repeated for *n* times. Or in other word, the evolution continues to the *n*th generation.

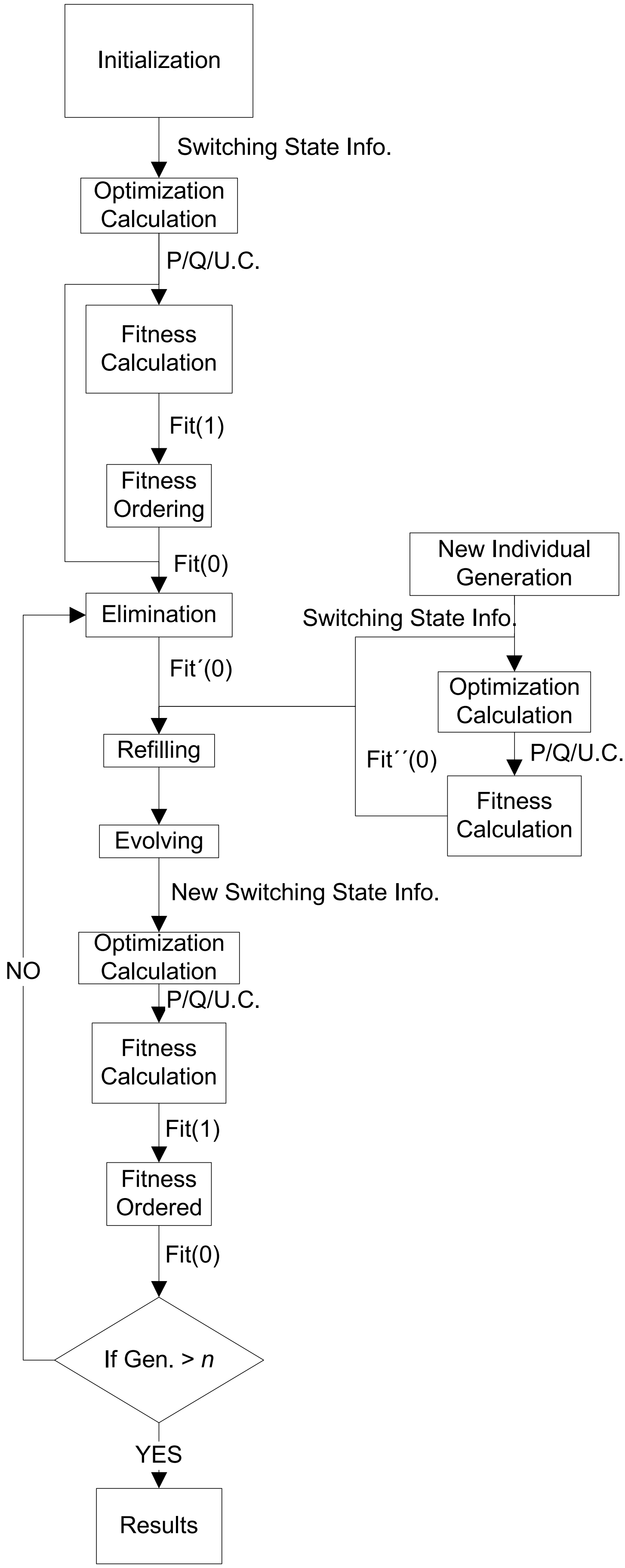

Figure 1-13 GA Process

Disadvantage of GA in this research

As a heuristic algorithm, the general advantage of GA is introduced in **Fehler! Verweisquelle konnte nicht gefunden werden.**. However during the application in this research, following disadvantages are found.

1. Multifarious Preparations before Optimization

As discussed in **Fehler! Verweisquelle konnte nicht gefunden werden.**, penalty factors, calculated by Equation 1-22, are introduced in GA. In order to get a convergent solution, plenty of groups of *p & R* are examined for each single Microgrid, as shown in Figure 1-10. Even more groups are needed to be examined if better performance in convergence is demanded.
Sizing of population and generation can be considered as an optional preparation to increase the algorithm speed or the algorithm accuracy. For Microgrids embedded by few DG units, the significance of population and generation size to optimization result is relatively low. Decreased value of population and generation can lead to the same result with increased speed. However, when DG number increases, larger size of population and generation is needed. Increased value of population or generation leads to sufficient genetic diversity or evolutions. Only with enough genetic diversity and evolutions, GA can find global or near global optimum solution, if there are any.

2. Relatively Low Optimization Speed

Number of DG units will influence the optimization speed greatly. When a Microgrid enlarges, the optimization speed decreases greatly. After many optimizations, it can be found that the needed time for GA algorithm increases logarithmically as shown in Figure 1-14. Time consumption becomes the main weakness for using GA method into further study.

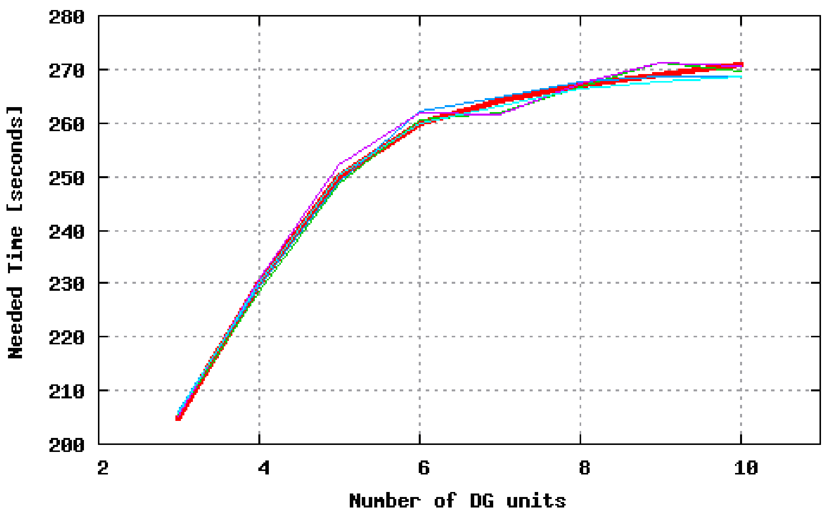

Figure 1-14 Required Time of GA Optimization

Heuristic Search (HS) Solution to the Scheduling Task

In this thesis, massive simulations and optimizations of Microgrid operation needed to be executed. The disadvantages discussed in 0 become the bottleneck of GA method for further application. To get a preparation-free and speed-improved optimization, Smart Scheduling Algorithm (SSA) is introduced and discussed in this section. Based on various performances of DG units represented by profit, SSA creates the priority list and behaves as a fast searching algorithm for optimal UC solution.

Hourly UC Optimization

In a liberalized market, all DG units compete with each other economically or technically. They are free to be turned on with grid connection or shut off. The economic optimization under a certain UC scenario is explained in **Fehler! Verweisquelle konnte nicht gefunden werden.**. Instead of evolutionary development (GA), iterative attempts are applied in SSA for optimal UC scenario search based on the experience from [15].

At the beginning of SSA, all DG units are assumed to be ON, the calculation of optimal power generation is performed. The profits of DG units are stored in a priority list, which shows the order of switch-off preference under economic terms. The definition of profit varies for different modes. [24]

- *Combined Mode and Economical Mode*

The profit represents the performance mainly in economic aspect. It should be noticed that in *Combined Mode*, profit also includes the contribution to active power loss and GHG emission reduction. A positive profit represents that this DG unit makes money. Adversely, a negative one means the DG unit loses benefit in this hour.

- *Technical Mode*

The profit represents the power loss in the Microgrid. A positive profit means this unit contributes to the power loss reduction. A negative one means this unit increases power loss due to the conversing power flow.

- *Environmental Mode*

The profit represents the emission cost of DG unit. A positive profit means this unit is relatively environmental friendly, compared to other units in GHG market or MV grid.

According to the priority list, DG units with bad profit (negative profit or relative low profit) are attempted to be switched OFF. Then the new ON/OFF state series is created and the profits are updated for comparison.

After optimization calculation for objectives (introduced in **Fehler! Verweisquelle konnte nicht gefunden werden.**), for the *Combined Mode* and *Technical Mode*, the updated information about voltage quality and line loading need to be checked firstly. If the network constraints cannot be satisfied, this unit is forced to be ON as a critical unit, no matter how much it costs. If the constraints can be satisfied, the profit is further compared with the former ON/OFF set.

Between the two alternatives, the one with a better profit is adopted. Then the next unit is tested with the same method.

For *Economic Mode* and *Environmental Mode*, as discussed in **Fehler! Verweisquelle konnte nicht gefunden werden.**, checks on violation of network operation are skipped. All DG units with negative profit are switched off.

Finally, the unit, which is critical to network operation, is forced to be ON or OFF. Others have the freedom to choose based on the profit they can have. After maximum $(n+1)$ (*n* is the number of DG units) tries, the most economical strategy is settled for this hour. The flow chart of this process is shown in Figure 1-15. After 24 iterations, the generation strategy for a whole day is fixed. In this step, duration constraint of DG unit is out of consideration. Therefore scheduling results from this step still need to be modified further in the next step, in order to fulfill duration constraint.

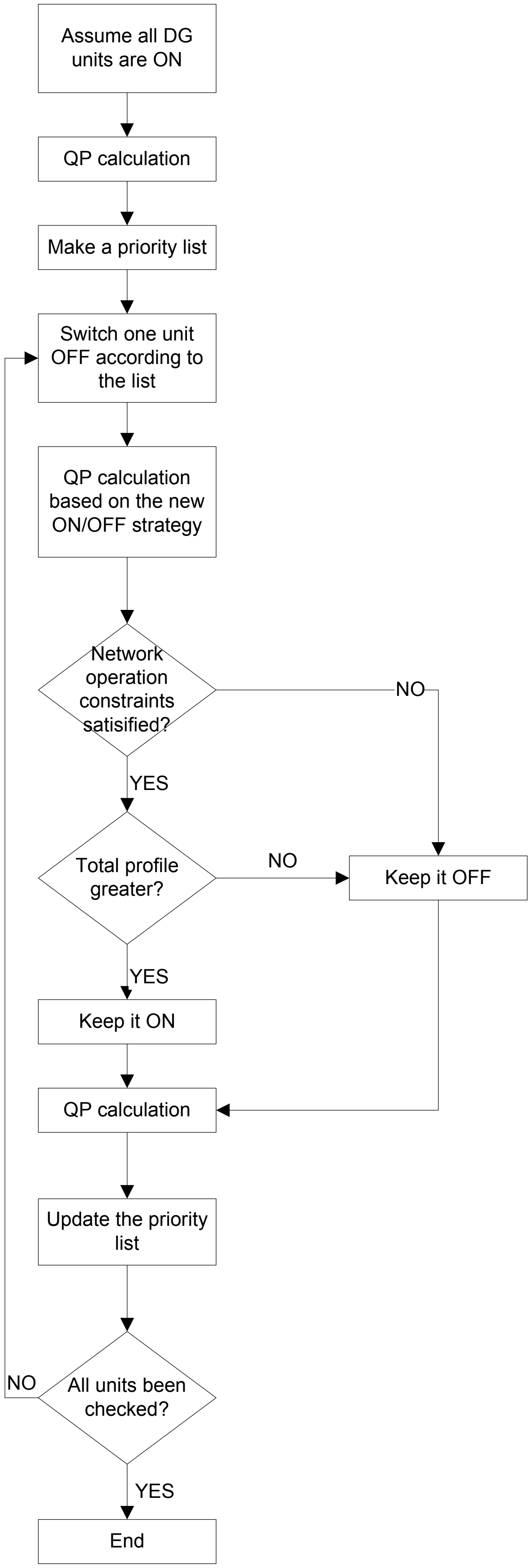

Figure 1-15 Most Economic Power Generation Strategy Settlement

Taking a general network with 6 DG units under *Combined Mode* as an example, three cases are mainly discussed in the following texts. Figure 1-16 shows the status of DG unit during this process. Blue color means this unit is waiting for examination. Red color means the unit is found as a critical unit for normal grid operation. And green color means the unit is noncritical and free to be switched ON or OFF according to its profit.

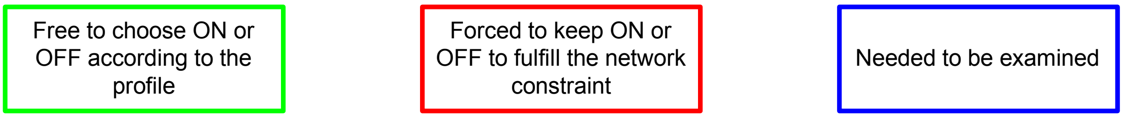

Figure 1-16 Color Index

Case 1: The market price is too low

In this case, all DG owners are unwilling to turn on their units, because they will loss benefit economically. However, the network constraints will be violated if all DG units are shut down. Therefore all units are forced to be ON at first. The deficit of each unit is represented by a negative profit. All units are tried to be shut down orderly. In the sample case of Figure 1-17, *Unit 3* and *Unit 6* are found as critical units. They are forced ON to keep normal grid operation, no matter how much it costs.

ID of unit	Profit
2	-672.1408
1	-670.4
3	-492
5	-321.4587
6	-284.4
4	-214.7051

ID of unit	Profit
3	-492
1	-392
5	-320.4713
6	-284.4
4	-214.0005
2	0

ID of unit	Profit
1	-392
5	-320.4713
6	-214.0005
4	-321.4587
2	0
3	-492

ID of unit	Profit
5	-318.1153
6	-283.8611
4	-212.0757
1	0
2	0
3	-492

ID of unit	Profit
5	-318.1153
6	-283.8611
4	-212.0757
1	0
2	0
3	-492

ID of unit	Profit
6	-267.0013
4	-209.5098
5	0
1	0
2	0
3	-492

ID of unit	Profit
4	-209.5098
5	0
1	0
2	0
3	-492
6	-267.0013

ID of unit	Profit
1	0
2	0
4	0
5	0
3	-492
6	-267.0013

Figure 1-17 Low Market Price with Dissatisfied Network Constraints

Case 2: The market price is high

In this case, most of units with positive profit are willing to turn on for benefits. However, full output from all DG units may cause the grid operation problem, such as overloading of lines or overvoltage, which are mainly caused by conversed power flow (especially in *Technical Mode*). The critical units, which are responsible for the operation failure, are searched and forced to shut down as shown in Figure 1-18.

In this test network, SSA finds that *Unit 1* is responsible for operation failure and shut it down. In the mean time, SSA finds *Unit 3* is a noncritical unit and keeps it on for positive profit. It can be viewed that, after shutting down *Unit 1*, the profits of every unit varies. The profits of *Unit 5* and *Unit 6* even turn into negative after *Unit 2* is shut down. Finally as shown in Figure 1-18, *Unit 1* and *Unit 2* are forced to be OFF to fulfill the network constraints; *Unit 3* and *Unit 4* are kept ON due to their positive profits; *Unit 5* and *Unit 6* are shut down to minimize the benefit loss.

ID of unit	Profit
3	18.63297
6	123.73548
5	129.3547
4	464.8093
1	535.95354
2	1011.6976

ID of unit	Profit
2	77.83162
6	135.5471
5	207.3035
4	535.95354
1	0
3	721.5174

ID of unit	Profit
6	-184.9024
5	-149.3222
1	0
2	0
4	54.455127
3	535.95354

ID of unit	Profit
6	-184.9024
5	-149.3222
1	0
2	0
4	54.455127
3	535.95354

ID of unit	Profit
5	-93.4759
1	0
2	0
6	0
4	59.292871
3	535.95354

ID of unit	Profit
1	0
2	0
5	0
6	0
4	79.715362
3	535.95354

Figure 1-18 High System Price with Dissatisfied Network Constraints

Case 3: The network constraints can be satisfied

In this case, DG units are free to behave themselves. Profit becomes the only aspect taken into consideration. Mentioned in Case 2, profits of DG units should be updated in every step. As shown in Figure 1-19, firstly *Unit 1* is shut down because of its negative profit. Although profit of *Unit 6* is positive, *Unit 6* is still examined to see if it contributes to the total profit. SSA shuts it down and calculates the total profit again. If the total profit increases, *Unit 6* is kept OFF.

Otherwise it is turned ON back. This comparison is applied in every unit with positive profit, from *Unit 6* to *Unit 2* orderly. In this sample, all units except *Unit 1* contribute to the total profit. Therefore, only *Unit 1* is shut down.

ID of unit	Profit
1	-463.68
6	28.236836
4	125.5
2	204.90697
5	283.41205
3	541.6

ID of unit	Profit
6	26.932791
4	125.5
5	280.35162
3	541.6
2	1033.5146
1	0

ID of unit	Profit
4	125.5
5	280.35162
3	541.6
2	1033.5146
1	0
6	26.932791

ID of unit	Profit
5	280.35162
3	541.6
2	1033.5146
1	0
6	26.932791
4	125.5

ID of unit	Profit
5	280.35162
3	541.6
2	1033.5146
1	0
6	26.932791
4	125.5

ID of unit	Profit
3	541.6
2	1033.5146
1	0
6	26.932791
4	125.5
5	280.35162

ID of unit	Profit
2	1033.5146
1	0
6	26.932791
4	125.5
5	280.35162
3	541.6

ID of unit	Profit
1	0
6	26.932791
4	125.5
5	280.35162
3	541.6
2	1033.5146

Figure 1-19 Satisfied Network Constraints

Duration Modification

After the first step discussed in 0, the objectives (economic, technical or environmental objective) can be achieved and network operation constraints can be fulfilled for *Combined Mode* and *Technical Mode*. Therefore the result obtained from 0 can be seen as the near-optimal operation strategy without consideration of DG ON/OFF duration limitation. In this section, constraint in continuous time domain, also call duration constraint, is checked and fulfilled.

As a preparation for duration modification, following information about ON duration and OFF duration is needed,

- ID of the DG unit
- Beginning hour of this duration (T_B)
- Time of this duration (*T*)

- Ending hour of this duration (T_E)
- ON or OFF status of this duration
- Total profit of this duration
- Switching Cost of this duration (Equation 1-3)

Here total profit with DG output from the first step in 0 is calculated by

$$Profit_i = \sum_{t=T_B}^{T_E} Rvn_i(t) - Cst_i(t)$$

Equation 1-27

where $Rvn_i(t)$ and $Cst_i(t)$ are explained in Equation 1-1 and Equation 1-2.

Notably, duration modification should be as less as possible, so that the final result can still represent the global (or near global) optimization. According to this principle, order, or called priority, for modification is necessary. Unlike 0, this priority list is not according to the profit of DG unit, but to its criticality to Microgrid. The times, which a DG unit acts as a critical unit to grid operation in the duration, are defined as the criticality. Criticality of each unit can be obtained from 0. For a certain DG unit, when its criticality to the grid increases, its possibility to be modified will decrease.

Various logics are applied in duration modification. Based on the obtained information from 0, SSA will examine every DG unit embedded in Microgrid and modifies its duration if it is necessary. Detailed logics about duration modification are discussed in the following texts, where objective unit refers to the unit under examination.

Combined Mode

1.) Check the ON duration

Case 1: $T \geq T_{up}(i)$

In this case, the ON/OFF duration constraint is met. In advance, the role of objective unit in every single hour is examined. If there are certain hours, even if one hour, in this period, when objective unit acts as a critical unit for keeping the network's normal operation, unit states in the whole period should not be modified. Because modification in this situation leads to a high risk of falling into an abnormal gird operation or further violated duration constraint, the economical efficiency in this period is abandoned.

If modification can be processed, which means objective unit never acts as a critical unit in this period, the profit of objective unit in this period is compared with the switching cost for this period. If the profit is greater then the switching cost, which means the unit can get benefits in this period, states of objective unit in this period is kept. Otherwise, it is switched OFF in this period to avoid the economic loss caused by switching. Detailed flow chart for this case is shown in Figure 1-20.

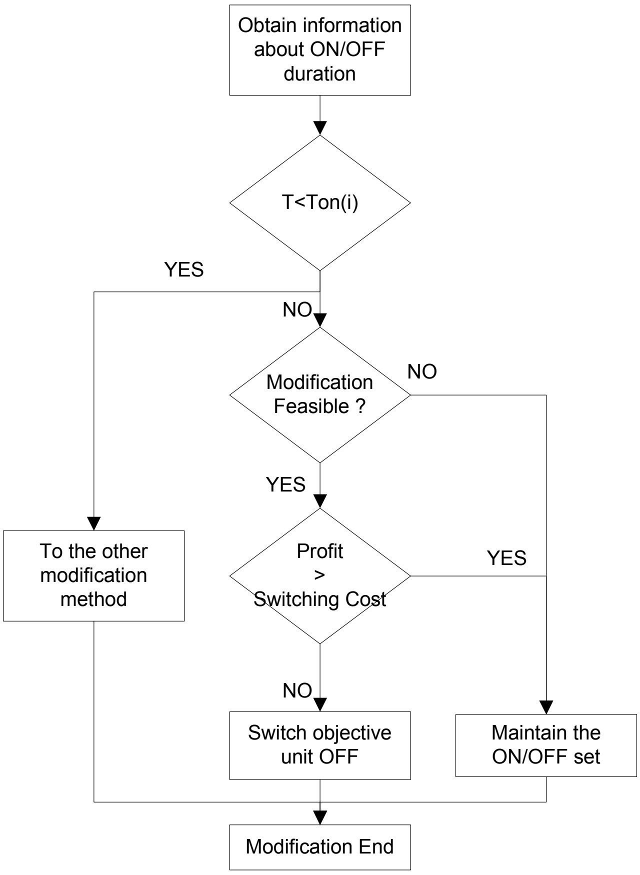

Figure 1-20 Flow chart for Combined Mode in Case 1

Case 2: $T < T_{up}(i)$

Obviously, duration constraint is dissatisfied. Like *Case 1*, the feasibility of duration modification is examined first. If this duration can be modified, SSA will turn the states of objective unit into OFF for the whole period. If not, further check for modification is applied. Firstly the feasibility of extending the ON duration is examined. With network constraints satisfied, there are three possible actions:

1. Objective Unit can be switched ON only in the previous hour.

2. Objective Unit can be switched ON only in the ensuing hour.

3. Objective Unit can be switched ON in both hours.

According to the above judgment, feasible alternatives are estimated by optimization calculation in **Fehler! Verweisquelle konnte nicht gefunden werden.** and extra costs of all alternatives are compared. The solution with minimum extra cost is adopted. If there is no feasible alternative, SSA fails in this optimization. This will be discussed in 0.

It should be noted that, when extending the ON duration, the risk of diverging from the near global optimization solution and further violating DG's duration constraint is relatively high. Therefore, the step of ON duration extension is one hour. In other words, for this case, after every single modification, the duration modification should be repeated with updated

ON/OFF duration information. Flow chart shown in Figure 1-21 describes this process in detail.

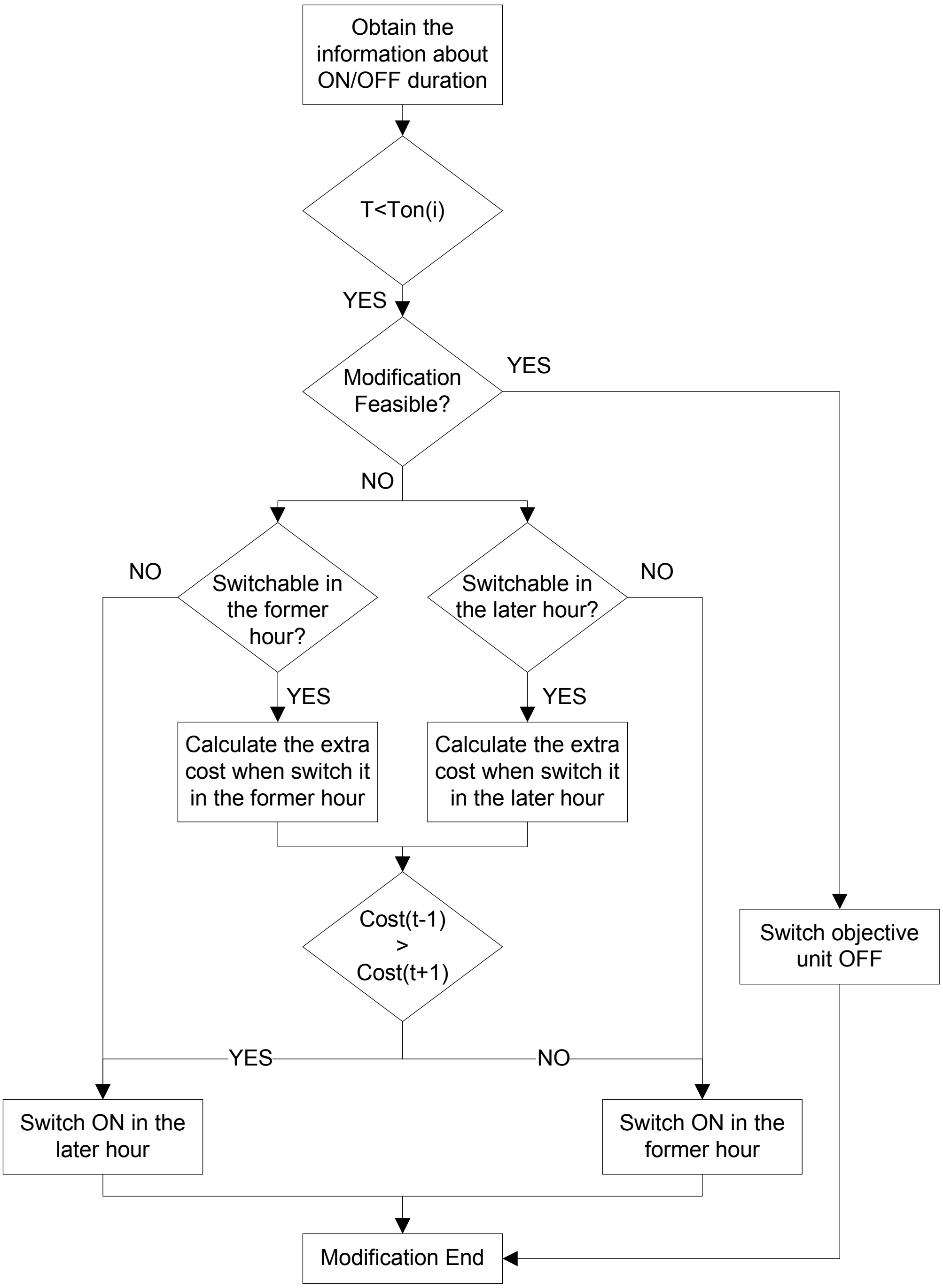

Figure 1-21 Flow Chart for Combined Mode in Case 2

2.) Check the OFF duration

The basic idea and algorithm of this check is similar to the check for ON duration. Both criticality to distribution network system operator and economic performance to DG owner are considered comprehensively. According to the discussion in 0, unit is switched OFF because of following two reasons:

1) Negative or relatively low profit

2) Violation of normal grid operation

Case 1: $T \geq T_{down}(i)$

In this case, the duration constraint is satisfied. If 1) is the only reason for OFF-duration, the additional generation cost (by Equation 1-1) for keeping objective unit on and the switching cost for this OFF-duration are compared. The strategy with less benefit loss is adopted. If 2) also responds to OFF-duration, the strategy is maintained for normal grid operation.

Case 2: $T < T_{down}(i)$

In this case, DG unit is forced to be ON if only 1) is the only reason of OFF-duration. If 2) is found as the reason for this OFF-duration, feasible solution (extending the OFF duration) is attempted like ON-duration-check. If there is no feasible solution to this violation, SSA fails in this optimization, which will be discussed in detail in 0.

Economic Mode

In this mode, network constraints are neglected. Therefore the duration modification is simplified. Only the economic performance of DG itself is compared among all alternative choices. The feasible solution which leads to an advanced profit is adopted. Figure 1-22 shows the flow chart of duration modification for *Economic Mode*.

Case 1: $T \geq T_{up}(i)\, or\, T \geq T_{down}(i)$

In this case, duration constraint is met. For duration modification, profit and switching cost for this duration are compared. The states of objective unit in this period will be changed in following situations:

- The benefit of power generation is offset by switching cost in ON-duration.
- The switching cost exceeds the additional generation cost in OFF-duration.

Case 2: $T < T_{up}(i)\, or\, T < T_{down}(i)$

Duration constraint is violated in this case. Two alternatives can be processed to satisfy the constraint in this case:

1) Changing the status of duration totally (ON into OFF or conversely)
2) Extending the duration until constraint satisfied

Obviously, both of the alternatives will result in total profit loss. The one with less loss is adopted.

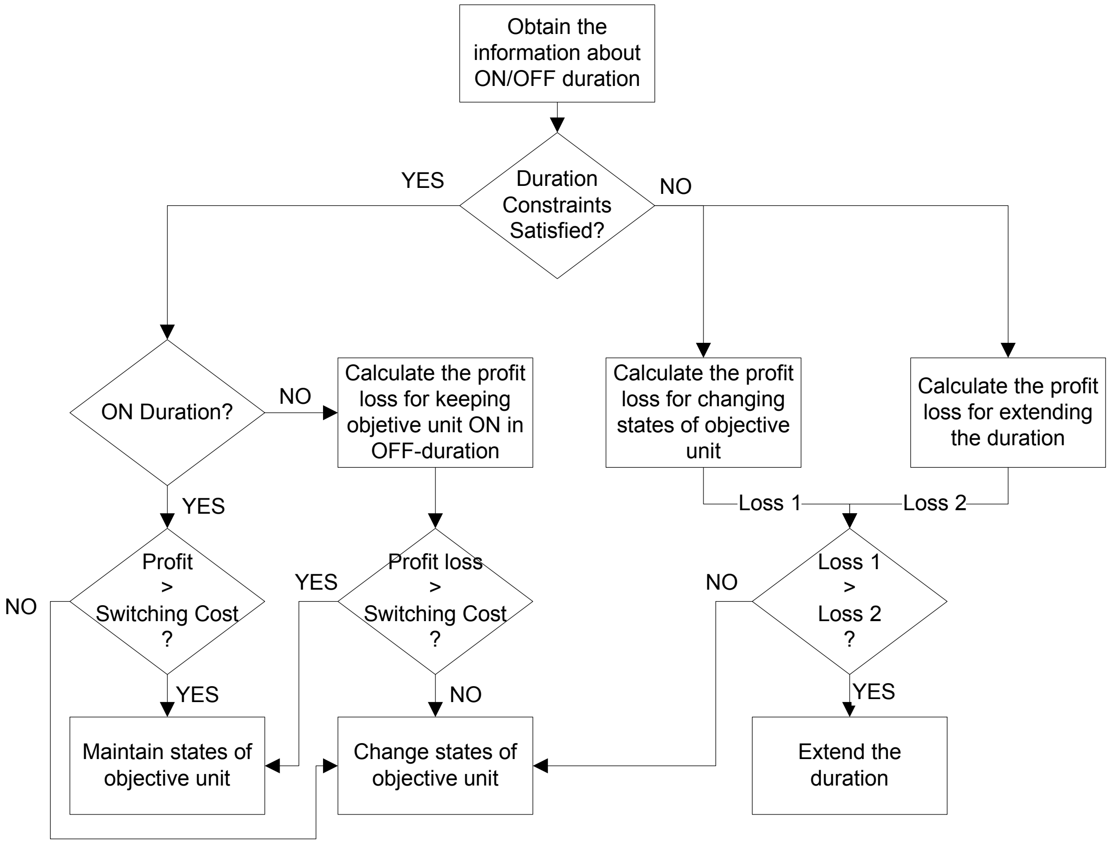

Figure 1-22 Duration Modification for Economic Mode

Environmental Mode

In this mode, the external emission cost is taken as a daily constant and the emission cost function is linear as discussed in **Fehler! Verweisquelle konnte nicht gefunden werden.**. This means that, in the first step of SSA introduced in 0, the unit which contributes to emission reduction will be ON in whole day. Therefore the duration constraint is satisfied naturally after 0. There is no need for duration modification for this mode.

Technical Mode

Case 1: $T \geq T_{up}(i)\, or\, T \geq T_{down}(i)$

In this case, duration constraint is satisfied and duration modification is not needed. As introduced in **Fehler! Verweisquelle konnte nicht gefunden werden.**, economic benefit is neglected in this mode. Scheduling strategy in this case should be maintained for minimization of active power loss.

Case 2: $T < T_{up}(i)\, or\, T < T_{down}(i)$

In this case, duration modification is needed. For OFF-duration, similar as *Combined Mode*, unit is switched OFF because of following two reasons:

(1) Negative profit

(2) Violation of normal grid operation

For ON-duration violation and OFF-duration violation caused only by the first reason, two alternatives as following can be processed to satisfy the constraint in this case:

1) Changing the states of objective unit totally (ON into OFF or conversely)

2) Extending the duration until constraint satisfied

Obviously, both of the alternatives will result in total profit loss. The one with less loss is adopted.

If the second reason is found responsible for OFF-duration, feasible solutions (extending the OFF duration) are attempted. All solutions are compared and the optimal one is adopted. Figure 1-23 shows the flow chart of duration modification for *Technical Mode*. If there is no feasible solution to this violation, SSA fails in this optimization, which will be discussed in detail in 0.

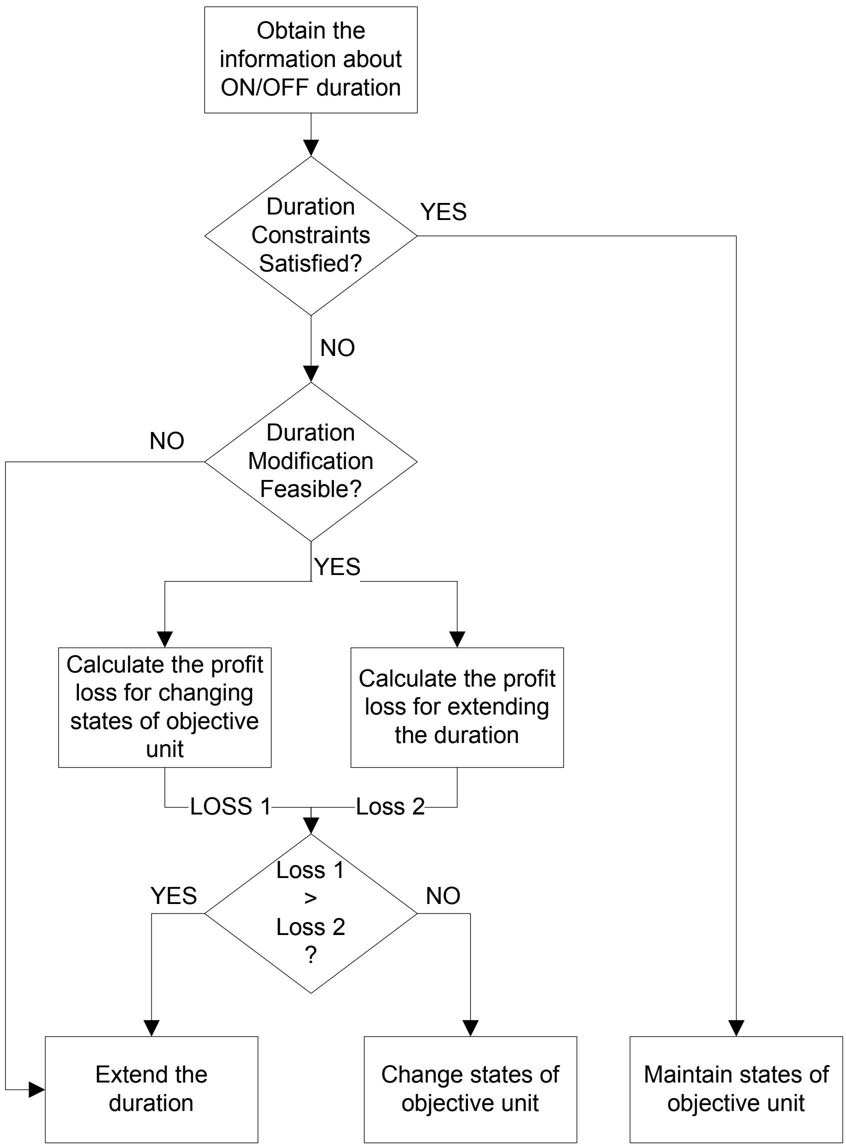

Figure 1-23 Duration Modification for Technical Mode

The test network shown in Figure 1-24, is taken for test in *Combined Mode*. In this network, 10 DG units, 2 CHP units, 4 PV units, 3 WT units and 1 storage device are embedded. The penetration level (P.L.) of DER units is listed as Table 1-3.

Type of Generation	P.L. of Units
DG	69.25%
MicroCHP	25%
MicroWT	25%
MicroPV	12.5%

Table 1-3 Penetration Level of DER units

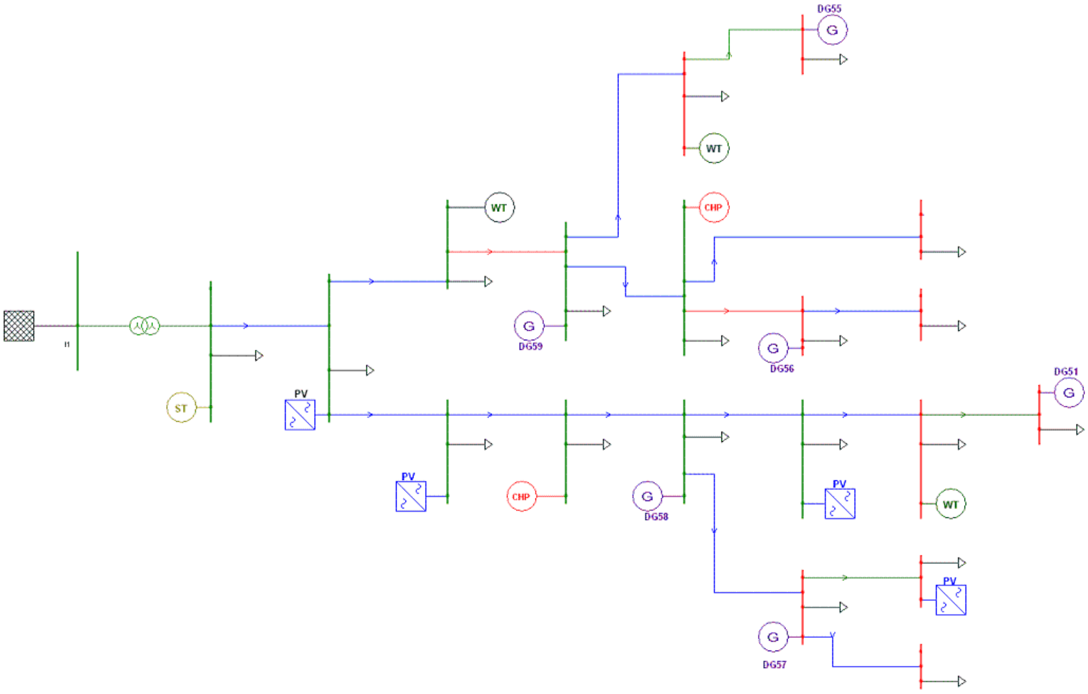

Figure 1-24 Test Network

Colored blocks in Figure 1-25 represent the status of DG units in the modification process. And the minimum ON/OFF duration for every unit is listed in Table 1-4. It can be found in Figure 1-26 that, the number of units, which need to be modified, is quite few.

DG name	Min. ON Duration [hour]	Min. OFF Duration [hour]
DG 1	7	7
DG 2	5	5
DG 3	4	4
DG 4	1	1
DG 5	4	4
DG 6	1	1

Table 1-4 Constraints for Minimum ON/OFF duration

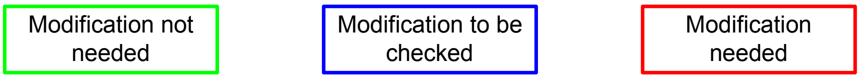

Figure 1-25 Color Index

0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	1	1	1	1	1	1	0
0	0	0	0	0	0	0	0	0	0	0	0	1	1	1	1	1	1	1	1	1	1	1	1	1
0	0	0	0	0	1	0	0	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
0	0	0	0	0	0	0	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
1	1	1	1	1	0	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	0

0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	1	1	1	1	1	1	0
0	0	0	0	0	0	0	0	0	0	0	0	1	1	1	1	1	1	1	1	1	1	1	1	1
0	0	0	0	0	1	0	0	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
0	0	0	0	0	0	0	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
1	1	1	1	1	0	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	0

Figure 1-26 Example of Duration Modification

Final Check

In this step, final check for constraints, both in time domain and simultaneous DG states is preformed. When error is found in this step, *Step 1* in 0 and *Step 2* in 0 are repeated until no error exists. This step can be considered as the final insurance for the whole algorithm. Actually, extreme case does exist, shown in Figure 1-27 (minimum OFF-duration is 2 hours for this unit), which will lead SSA into infinite loop. An infinite loop breaker is coded for this situation. The optimization process is stopped with a message and the detailed information about this failure is recorded. In this case, GA will introduce penalty factors. However SSA does not have penalty factors; therefore, SSA fails because there is no convergent solution under strict constraints. In practice, modification of SSA is not required, but the sizing and allocation of DG units.

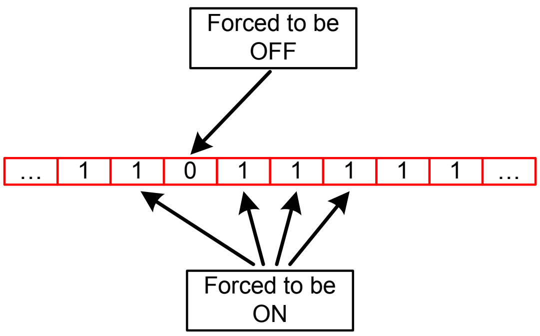

Figure 1-27 SSA Failure

GA and HS Comparison

The same Microgrid, shown in Figure 1-24, under combined, economic, environmental and technical modes is tested by both SSA method and GA method. The results are estimated and compared by not only the total fitness, but also technical, economical and environmental objectives.

Combined Mode

According to the descriptions in **Fehler! Verweisquelle konnte nicht gefunden werden.**, fitness can represent the comprehensive performance of Microgrid operation. Though fitness evolution is only considered in genetic algorithm (GA) in this research, the final fitness is still needed to be calculated in the smart schedule algorithm (SSA) for comparison with GA. According to the total fitness shown in Figure 1-28, SSA method and GA method can result in a similar Microgrid performance. There are differences in certain day. The reason for the differences is explained in detail in the following discussion of *Economic Mode*.

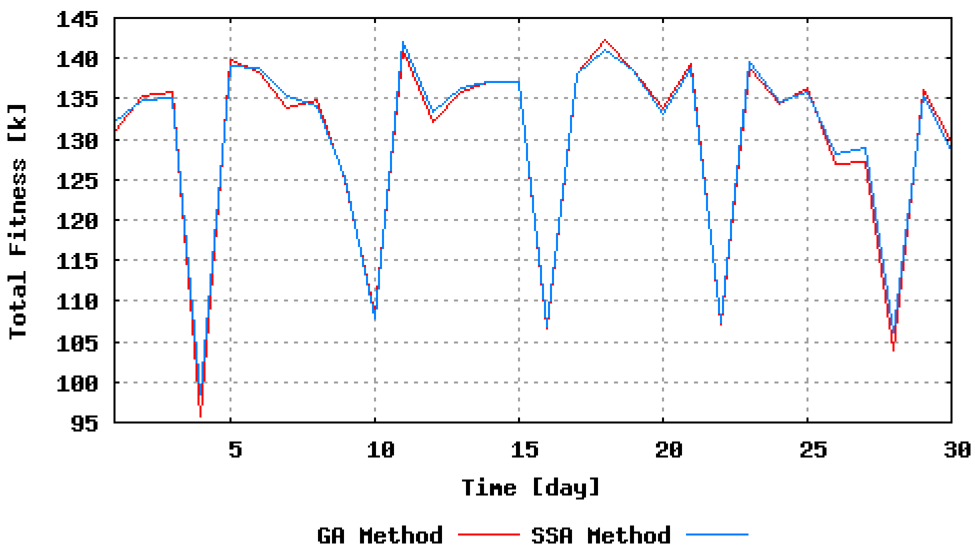

Figure 1-28 Total Fitness Comparison

Economic Mode

Economic benefit is the main aspect in this mode. It can be seen in Figure 1-29 that when compared to GA method, SSA method tends to adopt a relatively conservative strategy. It means that SSA method always tries to minimize the generation cost. This idea shows its advantage when the market price is low. However, under a high market price, GA method can lead to a higher profit than SSA method.

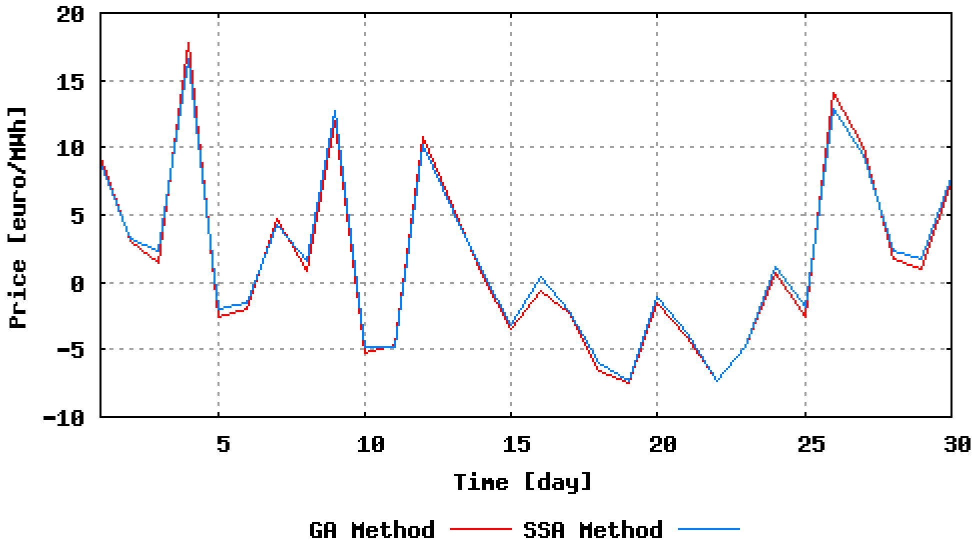

Figure 1-29 Economic Benefit Comparison

Technical Mode

In this mode, SSA method utilizes a strict regulation of DG operation. Hence, the power loss reduction is notable. GA method tends to adopt a more relaxed regulation. In other words, GA embodies the negotiation of interests between DSO and DG owners.

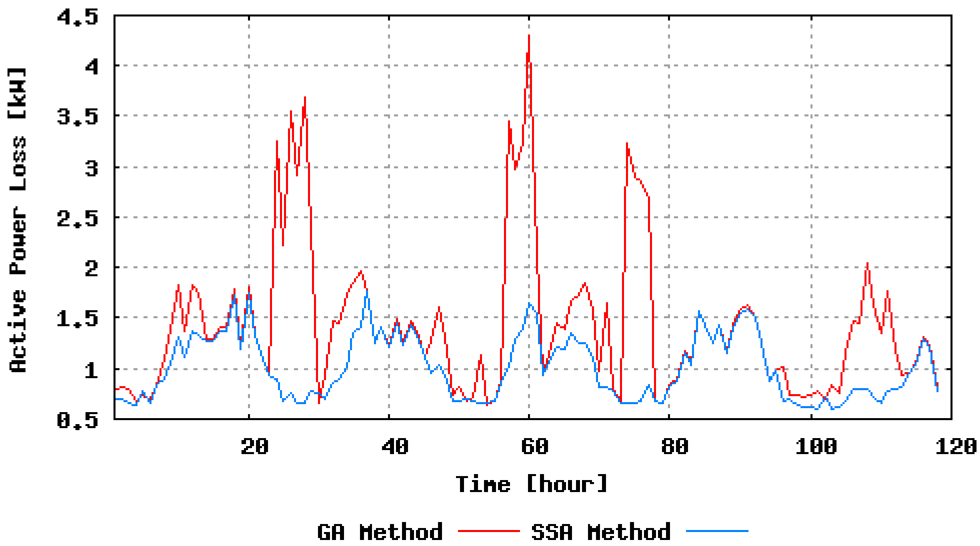

Figure 1-30 Total Power Loss Comparison

Environmental Mode

As mentioned in **Fehler! Verweisquelle konnte nicht gefunden werden.**, environmental benefits are represented by the reduction of GHG emission. Shown in Figure 1-31, the emission cost resulted by both SSA method and GA method are similar. In certain days, SSA method leads to less emission cost than GA method.

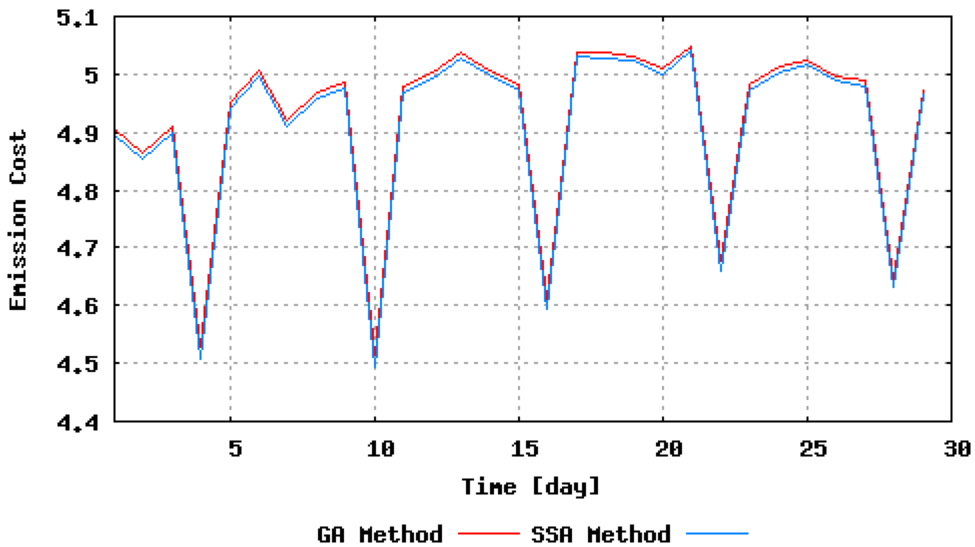

Figure 1-31 Emission Cost Comparison

It can be concluded from the above comparisons, that SSA method can achieve similar or even better (i.e. *Technical Mode*) optimization results when compared to GA method.

Considering the disadvantages of GA method discussed in 0, preparations, such as penalty factor tests and population & generation sizing for every Microgrid, can be skipped in SSA method.

In terms of execution speed, it takes GA method approximately 2 hours to optimize the Microgrid operation under *Combined Mode* for 31 days period. Relatively it only takes 15 minutes by SSA method. Time needed for daily optimization regarding the number of DG units is shown in Figure 1-32. Concerning improvements to the disadvantages of GA (0); SSA has its advantages in large-scale simulation tasks.

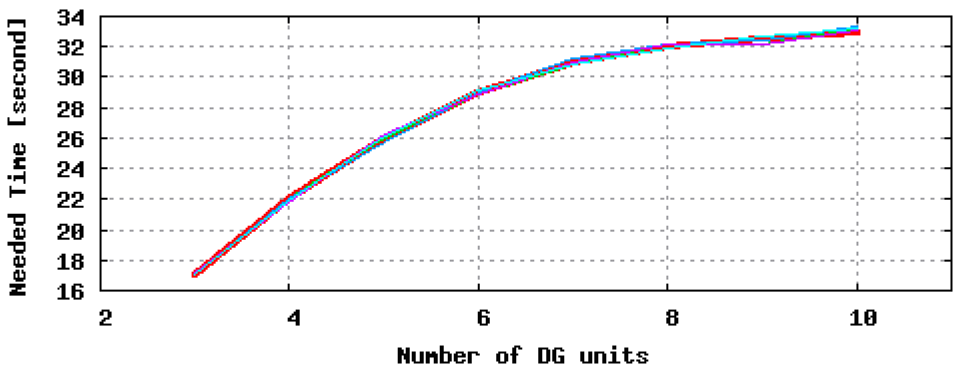

Figure 1-32 Required Time of SSA Optimization

Simulated Microgrid Schedules for Selected EU Scenarios

EU-Scale Scenario Definitions

All mathematic models and optimization methods are introduced in **Fehler! Verweisquelle konnte nicht gefunden werden.** and **Fehler! Verweisquelle konnte nicht gefunden werden.**. Based on them, various Microgrids and scenarios can be estimated and evaluated. In this chapter, simulations of different typical European Microgrids, which have been collected in frame of the European research project More Microgrids, are processed and the results are analyzed.

Analysis on Impacts of Microgrid Scheduling Modes

Greek Microgrid shown in Figure 1-33 is taken as a sample network. One reason is that various kinds of DER units are embedded. Another reason is its typical radial topology. In this Microgrid, there are 17 busbars, 15 power lines and 1 two-winding transformer. Concerning the DER units, there are 6 DG units, 2 micro WT units, 3 micro CHP units and 3 micro PV units. The penetration level of every kind of DER technology is listed in Table 1-5.

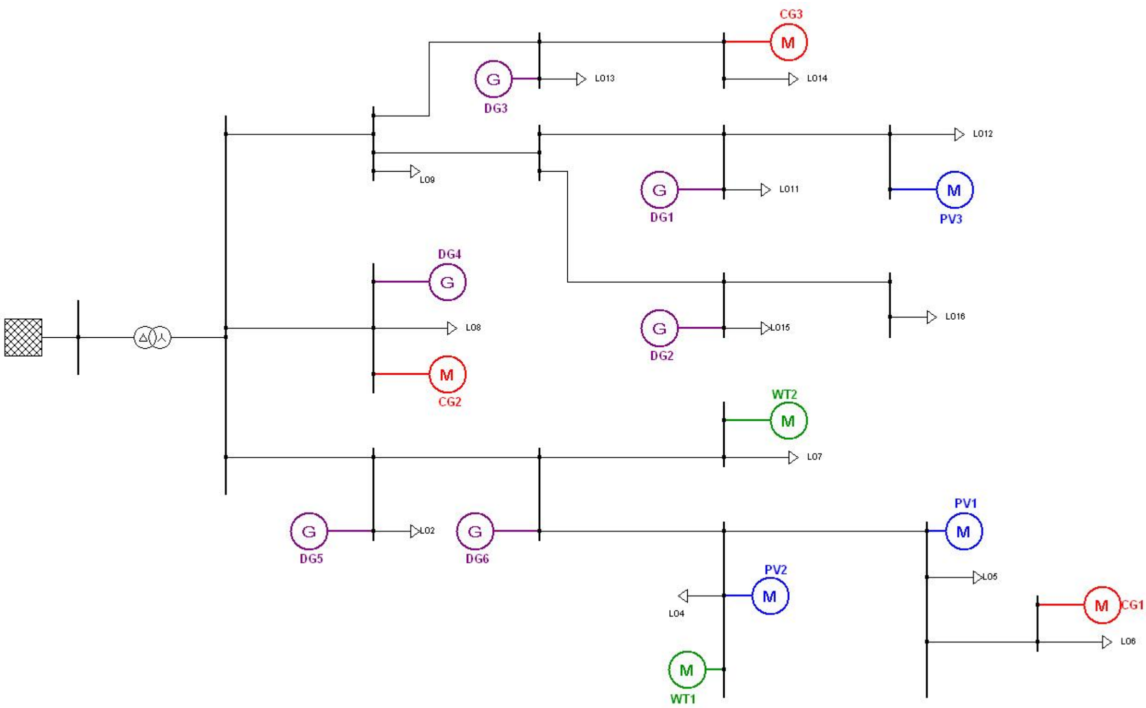

Figure 1-33 Greek Microgrid Embedded by DG Units

DER Technology	Penetration Level
DG	100%
MicroWT	30%
MicroCHP	36%

MicroPV	**36%**

Table 1-5 Penetration Level

The Microgrid operation is optimized for the whole year. As mentioned before, the results are evaluated under economic, technical, environmental and combined mode. They are compared in the following aspects, economic, technical and environmental aspect. Improvement in every aspect is calculated by:

$$Improvment = \frac{Original\,Value - Optimized\,Value}{Original\,Value}$$

Equation 1-28

Here 'original' means without Microgrid operation (original Microgrid from the research) and 'optimized' means after optimized Microgrid operation. Value refers to average annual value. In economic aspect, value refers to power price; in technical aspect, value refers to active power loss; in environmental aspect, value refers to GHG emission cost.

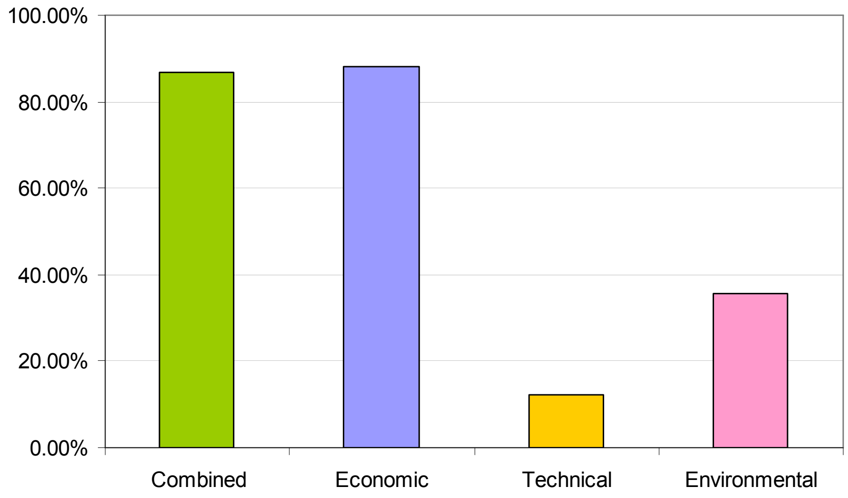

Figure 1-34 Power Price Reduction (Original Value: 50.099€/MWh)

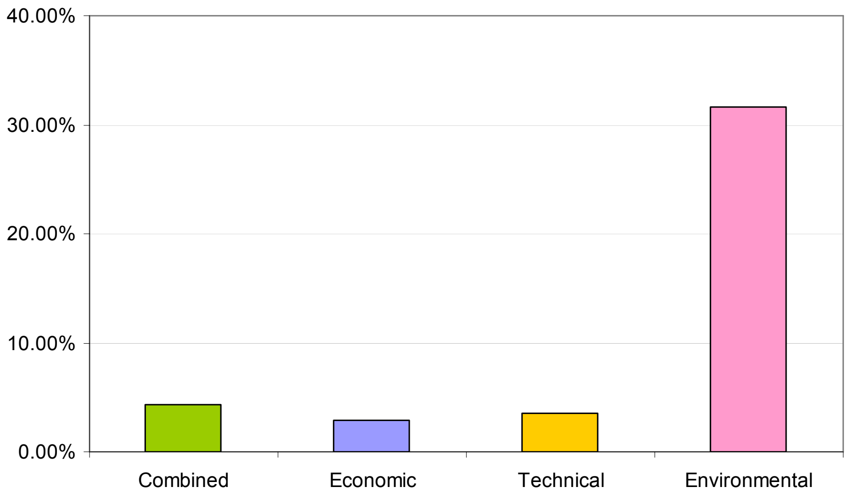

Figure 1-35 GHG Emission Reduction (Original Value: 6€/kW)

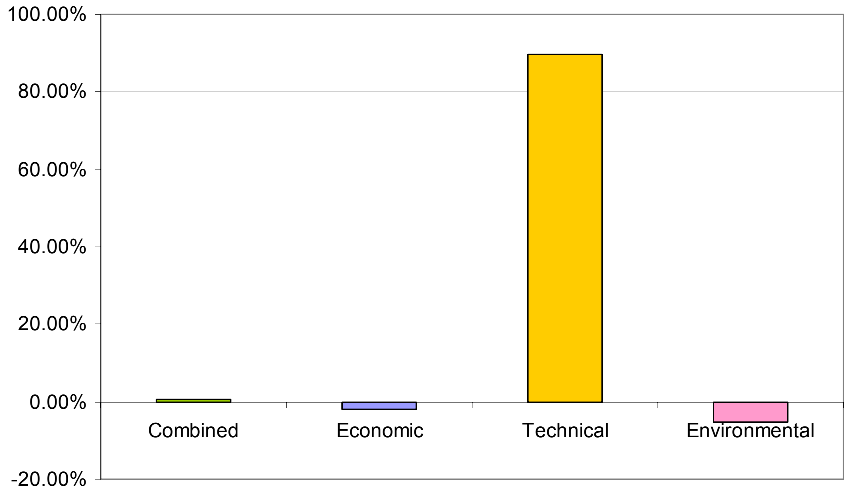

Figure 1-36 Power Loss Improvement (Original Value: 12.53kW/hour)

From the above figures, it can be seen that, combined mode optimization offers closest economic benefit to the economic option. Economic or environmental options bring the best results for DG owners or the society. However they are likely to cause technical issues in the grid such as under/over voltage or overloading of lines shown in Figure 1-37, which can not be accepted by DSO. Technical option fails to provide an economically attractive solution; neither can environmental solution achieve that. Combined optimization is a good compromise from the three partners in Microgrid (DSO, DG owner and environmental friendly) and performs reasonably well in all known aspects. [3] Therefore, *Combined Mode* is mainly studied for the further research.

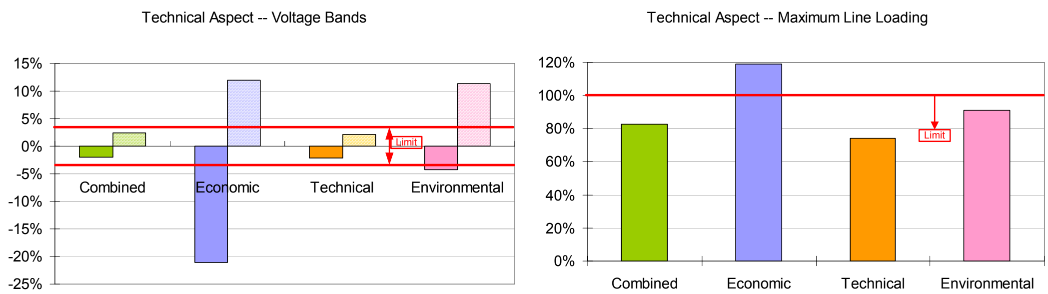

Figure 1-37 Line Loading and Voltage Band

Analysis on Impacts of DG/RES Penetration Levels

In 5.1, the benefits of Microgrid operation have been discussed. As concluded before, scheduling under pure *Economic Mode* and pure *Environmental Mode* is unpractical due to potential violations of network operation criteria. *Technical Mode* leads to the greatest benefit for DSO, but not for DG owners or the environment. Unlike economic, environmental or technical mode, *Combined Mode* leads to a result as negotiation among DSO, DG owners and environmental friendly, which brings the motivation of Microgrid operation. Therefore, *Combined Mode* is mainly discussed in both the scenario simulations and the following sections.

However, the penetration level of DG units and RES units varies country by country. There are many reasons for various P.L., such as the different national conditions, different climatic or geographic conditions, different Microgrid characteristics and etc. To simulate possible situations, various scenarios about DG penetration and RES penetration need to be defined. In this thesis, different scenarios mean different penetration levels of DG or RES units. Sizing and allocation of DER units for every scenario is shown in A.4.

The Greek Microgrid shown in Figure A-25 is taken as the test network again and 20 scenarios, listed in Table 1-6, are simulated. The columns represent the penetration level of RES units, from 20% to 100%. And the rows refer to the penetration level of DG units, from 40% to 100%. All simulations of scenarios are under *Combined Mode*.

P.L.	20%	40%	60%	80%	100%
40%	Scenario 1	Scenario 2	Scenario 3	Scenario 4	Scenario 5
60%	Scenario 6	Scenario 7	Scenario 8	Scenario 9	Scenario 10
80%	Scenario 11	Scenario 12	Scenario 13	Scenario 14	Scenario 15
100%	Scenario 16	Scenario 17	Scenario 18	Scenario 19	Scenario 20

Table 1-6 Scenario Definition

From Figure 1-38, it can be concluded that, with increased penetration of DG units and RES units, the economic benefit increases. Higher penetration level of DG means DG owners can choose the unit with higher capacity and lower generation cost. With highly decreased generation cost, the total economic benefit increases greatly.

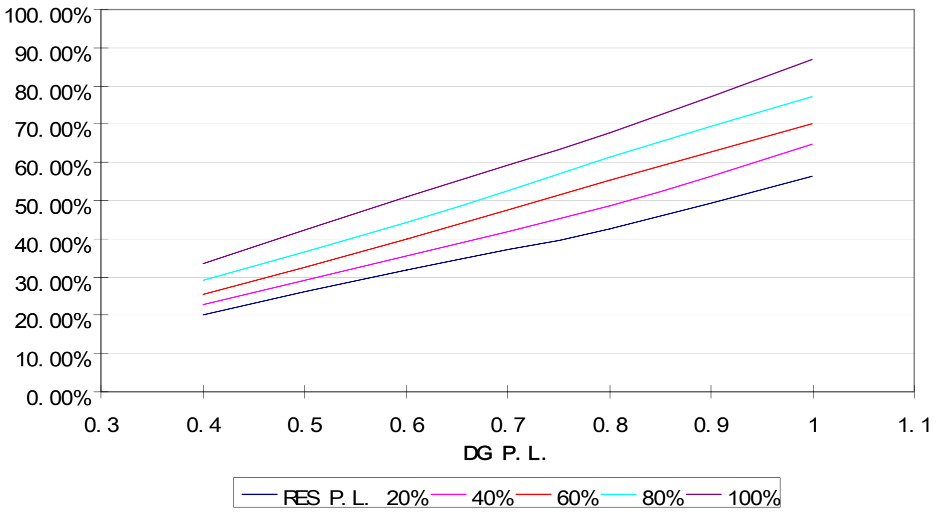

Figure 1-38 Power Price Reduction

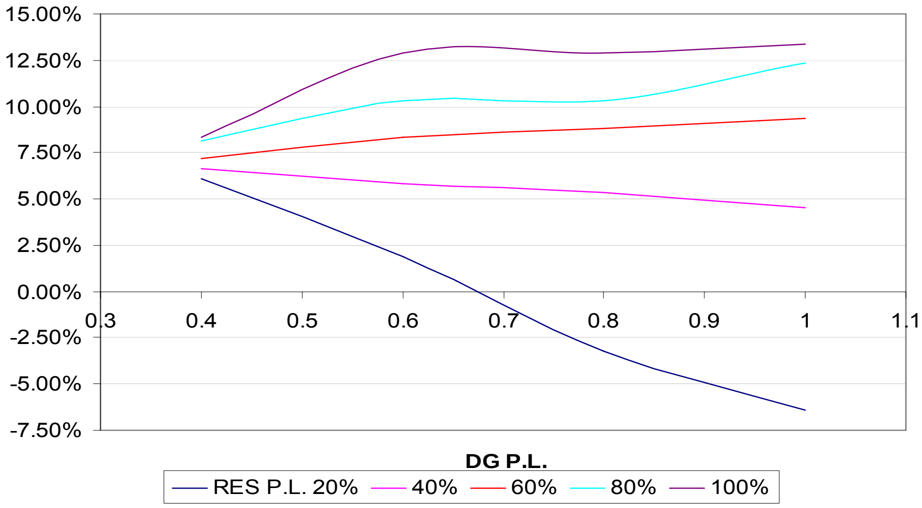

Figure 1-39 Emission Cost Reduction

However, concerning emission cost shown in Figure 1-39, when DG penetration increases continuously, the emission cost increases. With higher DG penetration level, DG units with high capacity will be embedded in Microgrid. However, in the meantime high capacity leads to high GHG emission. Therefore the total emission will increase with increased DG penetration level.

With a high penetration level of DG and RES, the power generation increases and will cause inversed power flow and lead to a high power loss. Shown in Figure 1-40, power loss improvement decreases if penetration level of DG and RES is too high.

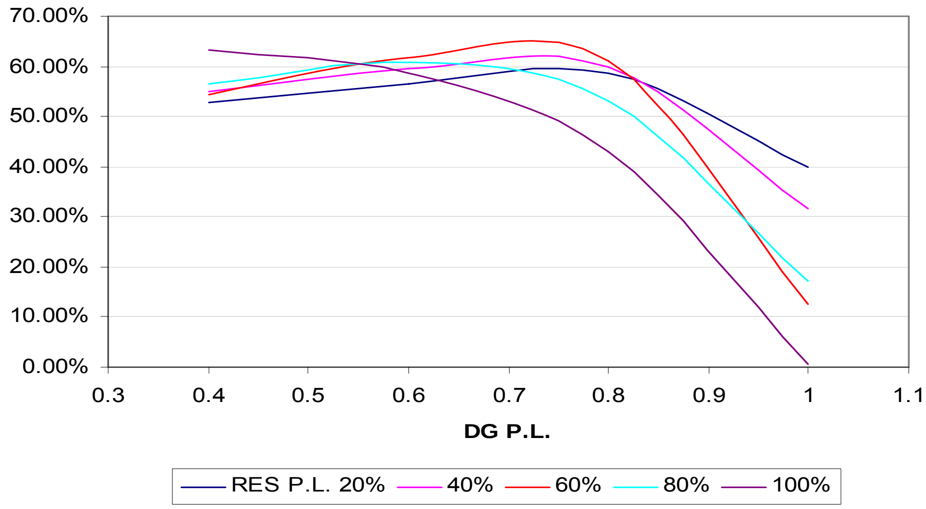

Figure 1-40 Power Loss Improvement

In summary, higher penetration level of DG and RES can lead to more benefit in economic aspect. However, too high penetration level of DG units will increases GHG emissions; and too high penetration level of DG and RES results in a decreased loss improvement. Therefore, a near-optimal penetration level of DG unit and RES unit should be searched for every Microgrid.

Results from *Economic Mode*, *Environmental Mode* and *Technical Mode* can be founded in the Appendix (A.3).

Comparative Analysis of EU-Scale Simulation Results

According to the conclusion in **Fehler! Verweisquelle konnte nicht gefunden werden.**, near optimal penetration levels of EU Microgrids are searched and utilized. The near optimal penetration level varies because of the various characteristics of different Microgrids. For every Microgrid, there are two scenarios: *Scenario 1* is DG-leaded Microgrid with auxiliary RES generation and *Scenario 2* is RES-leaded Microgrid with auxiliary DG generation. Definitions of *Scenario 1* and *Scenario 2* are listed in Table 1-7. The evaluated results from *Combined Mode* are mainly discussed to demonstrate the benefits which Microgrid operation will bring to EU. Results from other modes (economic, environmental and technical) can be founded in Appendix. Information about the Microgrids is listed in Appendix, in Table A-1 and from Figure A-25 to Figure A-47.

Nation Index	Scenario 1				Scenario 2			
	Penetration Level [%]				Penetration Level [%]			
	DG	CHP	PV	WT	DG	CHP	PV	WT
IT_R	135	25.26	16.84	8.42	50	63.16	58.95	12.63
IT_U	100	3.40	10.19	6.79	20	20.37	23.77	56.03
MA_R	100	3.74	24.28	14.01	50	26.15	50.43	23.35
NL_U	100	24.55	8.18	8.18	40	37.85	33.76	30.69
PL	120	32.68	6.54	9.80	70	49.02	22.88	45.76
UK_R	80	20.93	19.72	17.02	50	29.44	25.54	24.47
UK_U	80	18.45	7.10	24.12	50	30.86	20.22	28.38
PT_U	80	7.87	16.57	35.63	60	19.35	30.67	51.82
PT_SU	78	14.75	16.09	29.50	60	17.43	26.82	36.21
PT_R	80	13.56	19.72	8.22	48	19.72	27.93	34.92
DK	91	9.68	0	60.49	50	9.68	0	60.49
GR	80	21.69	21.69	18.07	60	27.71	28.92	24.10

Table 1-7 Penetration Level of Scenario 1 and Scenario 2

Same as **Fehler! Verweisquelle konnte nicht gefunden werden.**, all improvements are calculated by **Equation 1-28**. The original values of every EU Microgrid are listed in.

Nation Index	Avg. Power Price [€/MWh]	Emission Cost [€/kW]	Avg. Power Loss [kW/hour]
IT_R	55.898	6	20.65
IT_U	55.898	6	28.98
MA_R	67.996	6	34.87
NL_U	58.96	6	18.66
PL	78.88	6	17.56
UK_R	89.76	6	60.76
UK_U	89.76	6	49.88
PT_U	54.89	6	38.76
PT_SU	44.89	6	51.544
PT_R	44.89	6	59.64
DK	33.05	6	287.65
GR	50.099	6	12.53

Table 1-8 Original Values of EU Microgrids

From Figure 1-41, it can be seen that *Scenario 1* leads to an advanced performance in economic aspect. This is because unlike RES units, DG units are independent to primary resource disturbance and more controllable.

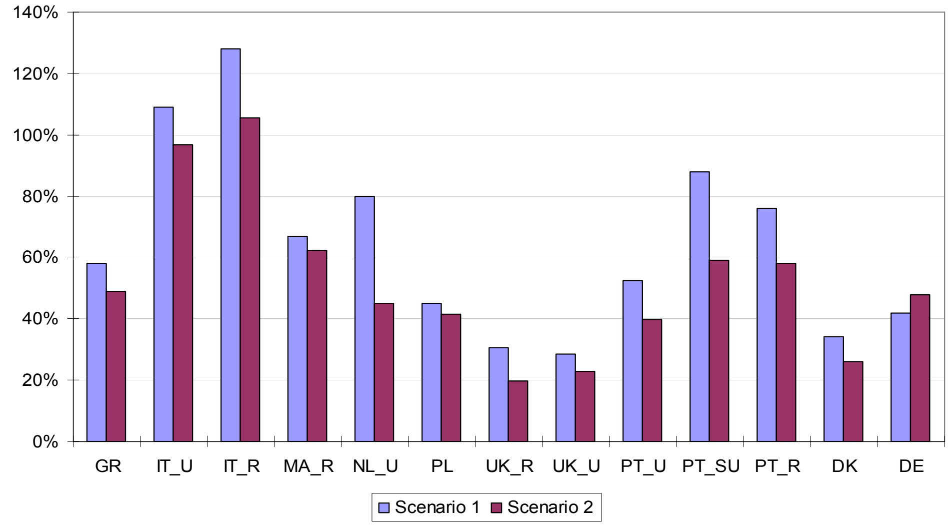

Figure 1-41 Economic Benefit

Increased RES penetration level in Microgrids will cause increased decentralization of power generation and decreased GHG emission. Therefore, shown in Figure 1-42 to Figure 1-44, *Scenario 2* leads to improved network performance, reflected by voltage, loading and active power loss; *Scenario 2* also results in an enhanced GHG emission reduction. However, in some Microgrid, the load is so heavy, that DG units with high pollution have to be installed. In this situation, the performance in emission reduction is bad.

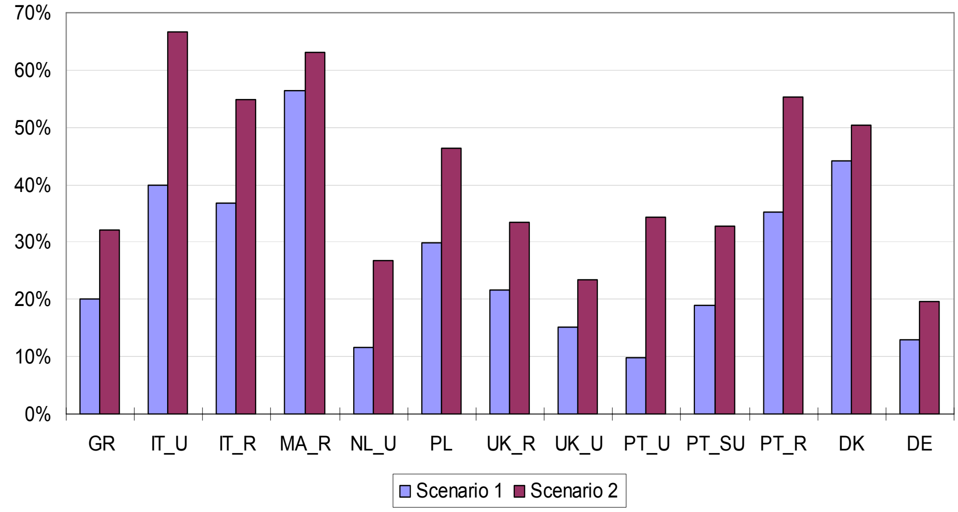

Figure 1-42 Line Loading Reduction

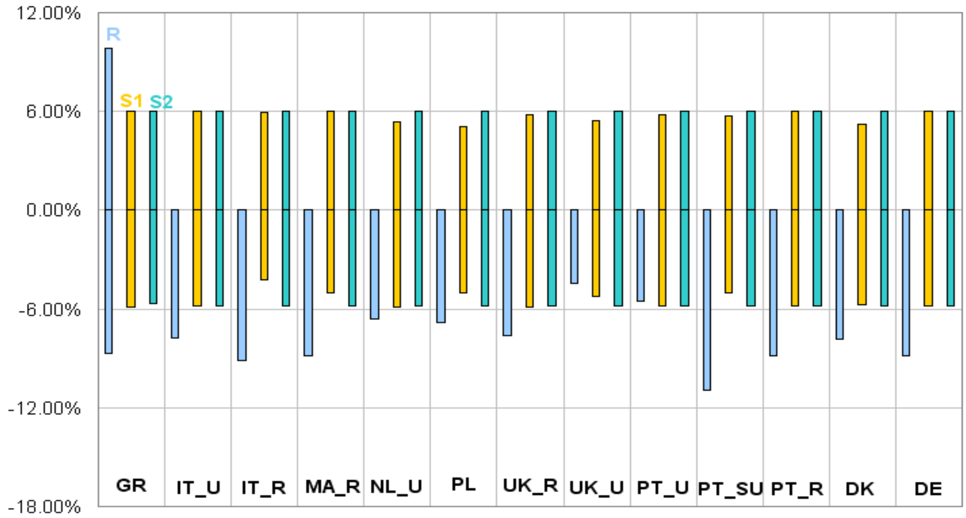

Figure 1-43 Voltage Band of Microgrids

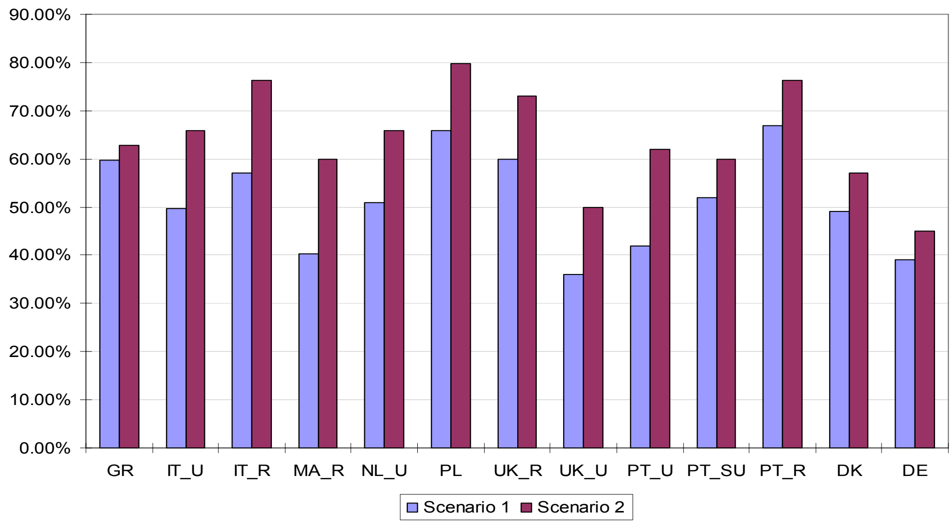

Figure 1-44 Active Power Loss Reduction

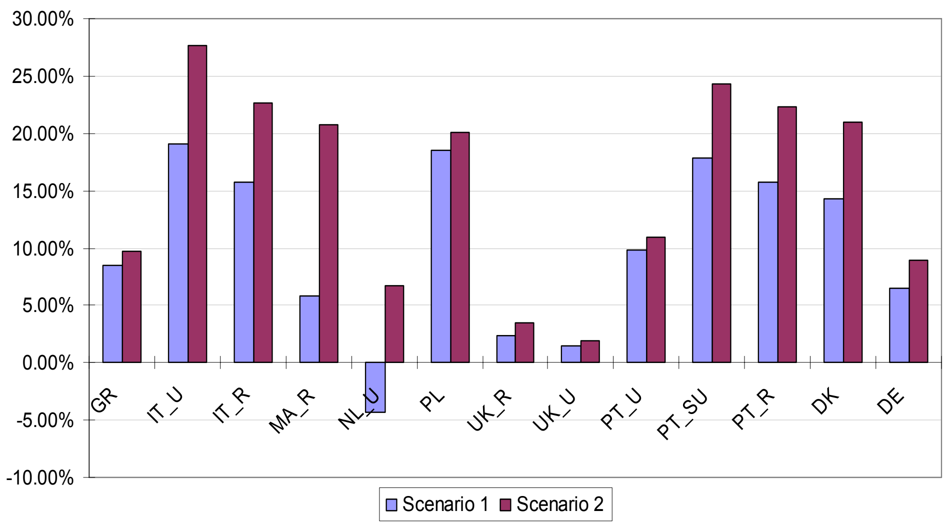

Figure 1-45 Emission Cost Reduction

With optimized operation, technical improvement of rural Microgrid is greater than urban Microgrid as shown in Figure 1-42 to Figure 1-44. For rural network, relatively high impedance of power lines result in great power loss and voltage drop through lines. With optimized Microgrid operation, loading ratio of power lines can be relaxed, which leads to decreased power loss and enhanced voltage performance. Therefore great technical improvements both on power loss and voltage can be achieved.

For Microgrids with heavy load, the economic benefit of optimized Microgrid operation under *Combined Mode* is greater than Microgrids with light load. DG units with larger capacity should be embedded in Microgrid with heavy loads. According to the discussion in **Fehler! Verweisquelle konnte nicht gefunden werden.**, DG units with larger capacity have lower generation cost. Therefore, greater economic benefit can be achieved by highly reduced power generation cost of DG. However, GHG emission is heavier for Microgrid with heavy load, such as Semi-Urban Microgrid of Portugal.

Economic Consideration of Control and Communication Costs

In practice, operation cost should be considered, whose net present value is defined as following:

$$
\begin{aligned}
&\text{Define:} \quad && K_{act} \text{ as total active control cost of a DER unit} \\
& && K_{ctrl} \text{ as investment cost of control device} \\
& && k_{met} \text{ as annual metering fee} \\
& && k_{com} \text{ as annual communication fee} \\
& && b \text{ as NPV factor}
\end{aligned}
$$

$$
\begin{aligned}
&\text{Then:} \quad && K_{act} = K_{ctrl} + \beta \cdot \left(k_{met} + k_{con}\right) \\
&\text{Assume:} \quad && \text{For } 2009,\ K_{ctrl} = 250€,\quad k_{met} = 100€/a,\quad k_{con} = 50€/a \\
& && \beta \cong 12.4622 \frac{1}{a} \\
& && K_{act}\_2029 = 75\% \cdot K_{act}\_2009,\quad K_{act}\_2049 = 50\% \cdot K_{act}\_2007
\end{aligned}
$$

$$
\text{Then:} \quad K_{act}\_2009 = 2119.33\ € \quad \Rightarrow \quad \begin{cases} K_{act}\_2029 = 1589.50\ € \\ K_{act}\_2049 = 1059.665\ € \end{cases}
$$

Table 1-9 shows the profit of EU Microgrids under optimized operation, before and after considering the operation cost. All the profits are converted into net present value, assuming life time is 20 years.

	Profit 1 [€][1]	Operation Cost [€]	Profit 2 [€][2]
GR	42326.60314	20663.5	21663.10314
IT_U	48682.33876	36558.5	12123.83876

[1] Profit before considering operation cost
[2] Profit after considering operation cost

IT_R	27450.82253	28611	-1160.177469
MA_R	41641.94017	95370	-53728.05983
NL_U	28771.69012	30200.5	-1428.809885
PL	10042.92582	23842.5	-13799.57418
UK_R	70914.29886	60401	10513.29886
UK_U	80270.95208	57222	23048.95208
PT_U	44567.25902	54043	-9475.740984
PT_SU	70780.06771	55632.5	15147.56771
PT_R	65161.82446	39737.5	25424.32446
DK	60685.5935	27021.5	33664.0935
DE	32585.05581	28611	3974.055814

Table 1-9 Profit Comparison for Scenario 2

	Profit 1 [€]	Operation Cost [€]	Profit 2 [€]
GR	61105.1709	17484.5	43620.6709
IT_U	31419.54007	23842.5	7577.040073
IT_R	15603.28051	12716	2887.280514
MA_R	51164.64283	46095.5	5069.142826
NL_U	139134.9781	22253	116881.9781
PL	19669.20768	19074	595.2076845
UK_R	125663.5532	38148	87515.55319
UK_U	108376.7908	41327	67049.79075
PT_U	74347.76477	38148	36199.76477
PT_SU	360698.4241	46095.5	314602.9241
PT_R	149422.8044	44506	104916.8044
DK	88977.24548	30200.5	58776.74548
DE	25562.41447	25432	130.4144746

Table 1-10 Profit Comparison for Scenario 1

Results shown in Table 1-9 and Table 1-10 are achieved in *Combined Mode*. As discussed in chapter **Fehler! Verweisquelle konnte nicht gefunden werden.**, *Scenario 2* leads to a better technical improvement. However lots of DER units are embedded in Microgrid in this scenario, which lead to increased operation cost. For certain Microgrids, the cost of optimized operation exceeds its benefits. Therefore the number of DER units should accord to the exact situation of every Microgrid. As shown in Figure 1-46, with less DER units embedded, *Scenario 1* shows its advantage in profit when considering operation cost of DER units.

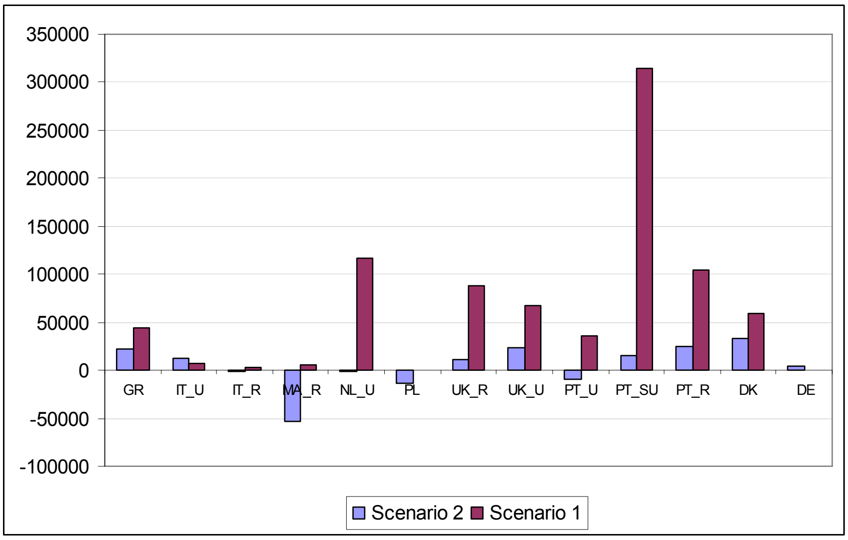

Figure 1-46 Profit Comparison between Scenarios Considering Operation Cost

References

[1] Aris Dimeas, Antonis Tsikalakis, Nikos Hatziagyriou, Rachel Li, Nick Jenkins, Olimpo Anaya-Lara, *Requirments Specifications for Microgrid Control*, More Microgrids – Advanced Architectures and Control Concepts for More Microgrids, Contract No. SES6-019864, Work Package B, 24-July-2006

[2] Christine Schwaegerl, Nikos Hatziargyriou, Antonis Tsikalakis, Anestis Anastasiadis, *Data Requirements and Methods for The Evaluation of Economic and Environmental Benefits of Microgrids*, Advanced Architectures and Control Concepts for More Microgrids, Contract, WPG – Task TG2, March 2007

[3] Alexandre Oudalov, Dimitris Georgakis, Stavros Papathanassiou, Nikos Hatziargyriou, *Report on the Microgrid Network Structures*, Advanced Architectures and Control Concepts for More Microgrids, , WPC, 2007-02-23

[4] João Abel Peças Lopes, André Madureira, Nuno Gil, *Data Requirements and Methodology for the Evaluation of Economic and Enviromental Benefits of Microgrids*, Advanced Architectures and Control Concepts for More Concepts, , WP G/H, 20-03-2007

[5] N. Hatziargyriou, A. Tsikalakis, J. Vlachogiannis, K. Papadogiannis, G. Kariniotakis, J. P. Lopes, J. Oyarzabal, C. Moreira, A. Madureira, I. Cobelo, *Microgrid Central Controller Strategies and Algorithms*, Microgrids Large Scale Integration of Micro-Generation to Low Voltage Grids, WP C, June 2004

[6] J. T. Saraiva, M. A. Matos, P. M. Costa, *Methods to Perform Loss Allocation Studies Review of the Literature and Simulations*, Large Scale Integration of Micro-Generation to Low Voltage Grids, WP G, May 2004

[7] G. Strbac, D. Pudjianto, *Markets for Trading Energy and Ancillary Services in Microgrids*, Large Scale Integration of Micro-Generation to Low Voltage Grids, WPG, June 2004

[8] J. T. Saraiva, *Alternative Formulation of the Adjustment Energy Market*, Large Scale Integration of Micro-Generation to Low Voltage Grids, WP G, January 2004

[9] S. A, Kazarlis, A. G. Bakirtzis, V. Petridis, *A Genetic Algorithm Solution to the Unit Commitment Problem*, IEEE Transactions on Power Systems, Vol. 11, No. 1, February 1996, pp.83-92

[10] A. Rudolf, R. Bayrleithner, *A Genetic Algorithm for Solving the Unit Commitment Problem of a Hydro-Thermal Power System*, IEEE Transactions on Power Systems, Vol. 14, No. 4, November 1999, pp.1460-1468

[11] K.A. Juste, H. Kita, E. Tanaka, J. Hasegawa, *An Evolutionary Programming Solution to the Unit Commitment Problem*, IEEE Transactions on Power Systems, Vol. 14, No. 4, November 1999, pp.1452-1459

[12] Charles W. Richter, Gerald B. Sheblé, *A Profit-Based Unit Commitment GA for the Competitive Environment*, IEEE Transactions on Power Systems, Vol. 15, No. 2, May 2000, pp.715-721

[13] Chuan-Ping Cheng, Chih-Wen Liu, Chun-Chang Liu, *Unit Commitment by Lagrangian Relaxation and Genetic Algorithms*, IEEE Transactions on Power Systems, Vol. 15, No. 2, May 2000, pp.707-713

[14] José Manuel Arroyo, Antonio J. Conejo, *A Parallel Repair Algorithm to Solve the Unit Commitment Problem*, IEEE Transactions on Power Systems, Vol. 17, No. 4, November 2002, pp.1216-1223

[15] Qiaoyhu Zhai, Xiaohong Guan, Jian Cui, *Unit Commitment with Identical Units: Successive Subproblem Solving Method Based on Lagrangian Relaxation*, IEEE Transactions on Power Systems, Vol. 17, No. 4, November 2002, pp.1250-1257

[16] Gianni Celli, Emilio Ghiani, Susanna Mocci, Fabrizio Pilo*, A Multiobjective Evolutionary Algorithm for the Sizing and Siting of Distributed Generation*, IEEE Transactions on Power Systems, Vol. 20, No. 2, May 2005, pp.750-757

[17] Li Tao, Mohammad Shahidehpour, *Price-Based Unit Commitment: A Case of Lagrangian Relaxation Versus Mixed Integer Programming*, IEEE Transactions on Power Systems, Vol. 20, No. 4, November 2005, pp.2015-2025

[18] Dimitris N. Simopoulos, Stavroula D. Kavatza, Costas D. Vournas, *Unit Commitment by an Enhanced Simulated Annealing Algorithm*, IEEE Transactions on Power Systems, Vol. 21, No. 1, February 2006, pp.68-76

[19] Miguel Carrión, José M. Arroyo, *A Computationally Efficient Mixed-Integer Lnear Formulation for the Thermal Unit Commitment Problem*, IEEE Transactions on Power Systems, Vol. 21, No. 3, August 2006, pp.1371-1378

[20] Seyed Hamid Hosseini, Amin Khodaei, Farrokh Aminifar, *A Novel Straightforward Unit Commitment Method for Large-Scale Power Systems*, IEEE Transactions on Power Systems, Vol. 22, No. 4, November 2007, pp.2134-2143

[21] Gerald F. Reid, Lawrence Hasdorff, *Economic Dispatch Using Quadratic Programming*, IEEE PES Winter Meeting, New York, January 28 – February 2,1973

[22] K. Aoki, T. Satoh, *Economic Dispatch with Network Security Constraints Using Parametric Quadratic Programming,* IEEE Transactions on Power Apparatus and System, Vol. PAS-101, No. 12 December 1982, pp.4548-4556

[23] K. Aoki, T. Satoh, *New Algorithms for Classic Economic Load Dispatch,* IEEE Transactions on Power Apparatus and Systems, Vol. PAS-103, No. 6, June 1984, pp.1423-1431

[24] T.A.A. Victoire, A.E. Jeyakumar, *Unit Commitment by a Tabu-Search-Based Hybrid-Optimization Technique*, IEE Proc.-Gener. Transm. Distrib., Vol. 152, No.4, July 2005 pp. 563-574

[25] Vo Ngoc Dieu, Weerakorn Ongsakul, *Augmented Lagrange Hopfield Network for Large Scale Economic Dispatch*, International Symposium on Electrical & Electronics Engineering 2007 – Oct 24, 25 2007 – HCM City, Vietnam, pp. 19-26

[26] Jorge Valenzula, Alice E. Smith, *A Seeded Memetic Algorithm for Large Unit Commitment Problems*,

[27] Roberto Caldon, Andrea Rossi Patria, Roberto Turri, *Optimal Control of A Distribution System with A Virtual Power Plant*,

[28] Abdullah Konak, David W. Coit, Alice E. Smith, *Multi-objective Optimization Using Genetic Algorithms: A Tutorial*,

[29] Antonio Frangioni, Claudio Gentile, *Solving Nonlinear Single-Unit Commitment Problems with Ramping Constraints*,

[30] A. H. Mantawy, Youssef L. Abdel-Magid, Shokri Z. Selim, *A New Genetic-Based Tabu Search Algorithm for Unit Commitment Problem*,

[31] I. G. Damousis, A. G. Bakirtzis, P. S. Dokopoulos, *A Solution to The Unit Commitment Problem Using Integer-Coded Genetic Algorithm*,

[32] João Catalão, Silvio Mariano, Victor Mendes, Luís Ferreira, *Unit Commitment with Environmental Considerations: A Practical Approach*, 15th PSCC, Liege, 22-26 August 2005, Session18, Paper 3, Page1-5

[33] Jorge Valenzuela, Mainak Mazumdar, *Probabilistic Unit Commitment Under A Deregulated Market*,

[34] Pierre Hansen, Nenad Mladenović, *A Separable Approximation Dynamic Programming Algorithm for Economic Dispatch with Transmission Losses*,

[35] Vo Ngoc Dieu, Weerakon Ongsakul, *Enhanced Merit Order and Augmented Lagrange Hopfield Network for Unit Commitment*, 15th PSCC, Liege, 22-26 August 2005, Session 18, Paper 2, Page 1-7

[36] Erlon Cristian Finardi, Edson Luiz da Silva, *Solving the Hydro Unit Commitment Problem via Dual Decomposition and Sequential Quadratic Programming*, IEEE Transactions on Power Systems, Vol.21, No. 2, May 2006, pp. 835-844

[37] T. Senjyu, A. Y. Saber, T. Miyagi, K. Shimabukuro, N. Urasaki, T. Funabashi, *Fast Technique for Unit Commitment by Genetic Algorithm Based on Unit Clustering*, IEE, 2005, Proceedings online no. 20045299

[38] A. Y. Saber, T. Senjyu, A. Yona, T. Funabashi, *Unit Commitment Computation by Fuzzy Adaptive Particle Swarm Optimisation*,

[39] A. Y. Saber, T. Senjyu, T. Miyagi, N. Urasaki, T. Funabashi, *Unit Commitment by Heuristics and Absolutely Stochastic Simulated Annealing*,

[40] B. Venkatesh, T. Jamtsho, H. B. Gooi, *Unit Commitment – A Fuzzy Mixed Integer Linear Programming Solution*,

[41] C. –L. Chiang, *Genetic-Based Algorithm for Power Economic Load Dispatch*,

[1] Liang Tao, *The Impact of Distributed Energy Resources on Future Networks*, Master Thesis, RWTH, IAEW, 2007

[2] L. Tao, C. Schwaegerl, N. Herrmann, *Impact of Microgrids Concept on Low Voltage Network Reliability*, CIRED Seminar, Smart Grids, 23./24.06.2008, Frankfurt

[3] Liang Tao, EU-Scale Microgrid Scheduling under Varied Criteria, More Microgrid Internal Report, Dec. 2008, Nürnberg

[4] N. Hatziargyriou, et al., *Microgrids – Large Scale Integration of Microgeneration to Low Voltage Grids*, CIGRE 2006, paper C6~309

[5] C. Schwaegerl, et al. – *Advanced Architecture and Control Concepts for More Microgrids*, internal report, November 2008

[6] Sayeed Salam, *Unit Commitment Solution Methods*, Proceedings of World Academy of Science, Engineering and Technology, Volume 26, December 2007, ISSN 1307-6884

[7] K. M. Maribu, *Modeling the Economics and Market Adoption of Distributed Power Generation*, doctoral thesis, Norwegian University of Science and Technology, Department of Electrical Power Engineering, June 2006

[8] S. Abu-Sharkh, et al., *Microgrids: distributed on-site generation*, technical report 22, Tyndall Centre for Climate Change Research, March 2005

[9] Edwin Haesen, et al., *Optimal Placement and Sizing of Distributed Generator Units using Genetic Optimization Algorithms*, May 2, 2005

[10] W. Rosehart, E. Nowicki, *Optimal Placement of Distributed Generation*, 14th PSCC, Sevilla, Session 11, Paper 2, 24~28 June 2002

[11] M. AlRashidi, M. El-Hawary, *Economic Dispatch with Environmental Considerations using Particle Swarm Optimization*, Power Engineering, 2006 Large Engineering Systems Conference, Page 41~46, ISBN 1-4244-0556-4

[12] D. Zhang, P. Luh, Y. Zhang, *A Bundle Method for Hydrothermal Scheduling*, IEEE Transactions on Power Systems, Volume 14, Issue 4, Pages 1355~1361, Nov. 1999

[13] M. AlRashidi, M. El-Hawary, *Emission-Economic Dispatch using a Novel Constraint Handling Particle Swarm Optimization Strategy*, Electrical and Computer Engineering, 2006. CCECE'06. Canadian Conference, Page 664~669, May 2006

[14] X. Guan, et al., *An Optimization-Based Algorithm for Scheduling Hydrothermal Power Systems with Cascaded Reservoirs and Discrete Hydro Constraints*, IEEE Transactions on Power Systems, Volume 12, Issue 4, Page 1775~1780, Nov. 1997

[15] A. Conejo, J. Arroyo, et al., *Self-Scheduling of a Hydro Producer in a Pool-Based Electricity Market*, IEEE Transactions on Power Systems, Vol. 17, No. 4, Page 1265~1272, Nov. 2002

[16] B. Parsannan, P. Luh, H. Yan, J. Palmberg, L. Zhang, *Optimization-Based Sale Transactions and Hydrothermal Scheduling*, IEEE Transactions on Power Systems, Volume 11, Issue 2, Page 654~660, May 1996

[17] G. Wang, et al. *A Practical Mixed Integer Linear Programming Based Approach for Unit Commitment*, Power Engineering Society General Meeting, 2004, IEEE, Volume, Issue, 6-10 June 2004, Pages 221~225 Vol.1

[18] W.J. Klunne, *Microhydropower*, 2009

[19] Joint Research Centre, *Photovoltaic Solar Electricity Potential in European Countries*, European Communities, 2006

[20] A. Rudolf, R. Bayrleithner, *A Genetic Algorithm for Solving the Unit Commitment Problem of a Hydro-Thermal Power System*, IEEE Transactions on Power Systems, Vol. 14, No. 4, November 1999

[21] S. Kazarlis, A. Bakirtzis, V. Petridis, *A Genetic Algorithm Solution to the Unit Commitment Problem*, IEEE Transactions on Power System, Vol. 11, No. 1, Feb. 1996

[22] J. Fan, L. Zhang, J. McDonald, *Enhanced Techniques on Sequential Unit Commitment with Interchange Transactions*, IEEE Transactions on Power Systems, Vol. 11, No. 1, Feb. 1996

[23] K. Juste, et. al., An *Evolutionary Programming Solution to the Unit Commitment Problem*, IEEE Transactions on Power Systems, Vol. 14, No. 4, Nov. 1999

[24] C. Richter, G. Sheblé, *A Profit-Based Unit Commitment GA for the Competitive Environment*, IEEE Transactions on Power Systems, Vol. 15, No. 2, May 2000

[25] C. Cheng, C.W. Liu, C.C. Liu, *Unit Commitment by Lagrangian Relaxation and Genetic Algorithms*, IEEE Transactions on Power Systems, Vol. 15, No. 2, May 2000

[26] J. Arroyo, A. Conejo, *A Parallel Genetic Algorithm to Solve the Unit Commitment Problem*, IEEE Transactions on Power Systems, Vol. 17, No. 4, Nov. 2002

[27] Q. Zhai, X. Guan J. Cui, *Unit Commitment with Identical Units: Successive Subproblem Solving Method Based on Lagrangian Relaxation*, IEEE Transactions on Power Systems, Vol. 17, No. 4, Nov. 2002

[28] G. Celli, et al., *A Multiobjective Evolutionary Algorithm for the Sizing and Siting of Distributed Generation*, IEEE Transactions on Power Systems, Vol. 20, No. 2, May 2005

[29] T. Li, M. Shahidehpour, *Price-Based Unit Commitment: A Case of Lagrangian Relaxation Versus Mixed Integer Programming*, IEEE Transactions on Power Systems, Vol. 20, No. 4, Nov. 2005

[30] D. Simopoulos, S. Kavatza, C. Vournas, *Unit Commitment by an Enhanced Simulated Annealing Algorithm*, IEEE Transactions on Power Systems, Vol. 21, No. 1, Feb. 2006

[31] M. Carrión, J. Arroyo, *A Computationally Efficient Mixed-Integer Linear Formulation for the Thermal Unit Commitment Problem*, IEEE Transactions on Power Systems, Vol. 21, No. 3, Aug. 2006

[32] S. Hosseini, A. Khodaei, F. Aminifar, *A Novel Straightforward Unit Commitment Method for Large-Scale Power System*, IEEE Transactions on Power Systems, Vol. 22, No. 4, Nov. 2007

[33] E. Finardi, E. Silva, *Solving the Hydro Unit Commitment Problem via Dual Decomposition and Sequential Quadratic Programming*, IEEE Transactions on Power Systems, Vol. 21, No. 2, May 2006

[34] X. Guan, et al., *Optimization-Based Scheduling of Hydrothermal Power Systems with Pumped-Storage Units*, IEEE Transactions on Power Systems, Vol. 9, No. 2, May 1994

[35] C. Li, et al. *Hydro Unit Commitment in Hydro-Thermal Optimization*, IEEE Transactions on Power Systems, Vol. 12, No. 2, Ma 1997

[36] P. Chen and H. Chang, *Genetic Aided Scheduling of Hydraulically Coupled Plants in Hydro-Thermal Coordination*, IEEE Transactions on Power Systems, Vol. 11, No. 2, May 1996

[37] P. Sotkiewicz, J. Vignolo, *Allocation of Fixed Costs in Distribution Networks with Distributed Generation*, IEEE Transaction on Power Systems, Vol. 21, No. 2, May 2006

[38] E. Khodaverdian, et al., *Semi-rigorous Thermal Unit Commitment for Large Scale Electrical Power Systems*, IEE Proceeding-Generation, Transmission & Distribution, Vol. 133, No. 4, 1986

[39] L. Baptistella, J. Geromel, *Decomposition Approach to Problem of Unit Commitment Schedule for Hydrothermal Systems*, IEE Proceedings-D, Vol. 127, No.6, 1980

[40] R. Bellman, S. Dreyfus, *Applied Dynamic Programming*, Princeton University Press, New Jersey, 1962, Page 4~16

[41] A. Muckstadt, S. Koenig, *An Application of Lagrangian Relaxation to Scheduling in Power-Generation Systems*, Operation Research, Vol. 25, No. 3, Page 387~403, 1977

[42] S. Khennas, A. Barnett, *Best Practices for Sustainable Development for Micro Hydro Power In Developing Countries*, The Department for International Development, UK and the World Band, Final Synthesis Report, Contract R7215, March 2000

[43] Dragoslav R., Risto A., Rubin T., *Voltage Correction Power Flow, IEEE Transactions on Power Systems*, Vol. 9, No. 2, page 1056 ~ 1062, April 1994

[44] Chen G.J., Li K.K., Chung T.S., Tang G.Q., *An Efficient Two-stage Load Flow Method for Meshed Distribution Networks*, IEEE International Conference on Advances in Power System Control, Operation and Management (APSCOM), 2000

Appendix

A.1 Results for scenarios of Greek Microgrid

A.1.1 Economic Mode

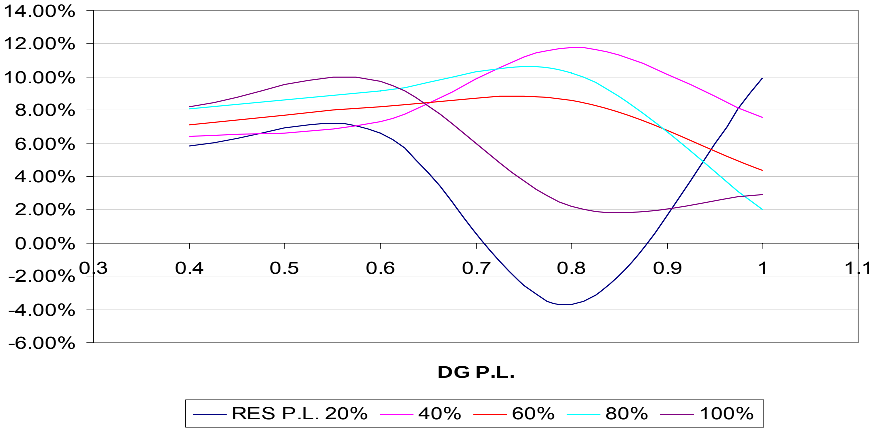

Figure A-1 Emission Cost Reduction (Original Value: 6€/kW)

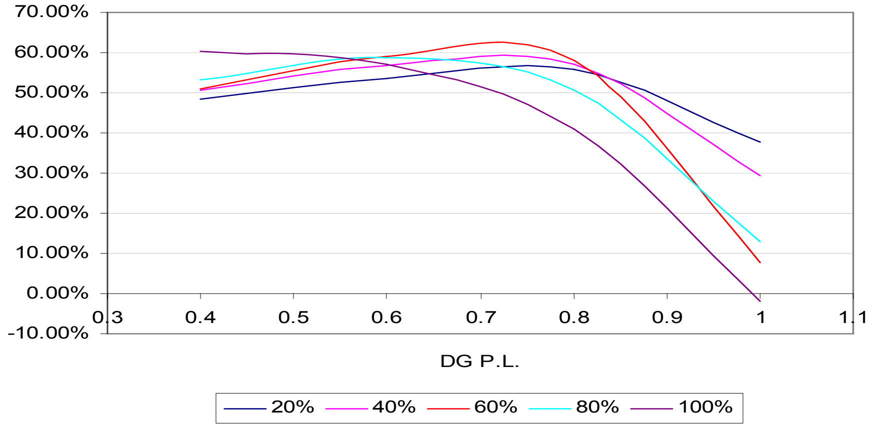

Figure A-2 Power Loss Improvement (Original Value: 12.09kW/hour)

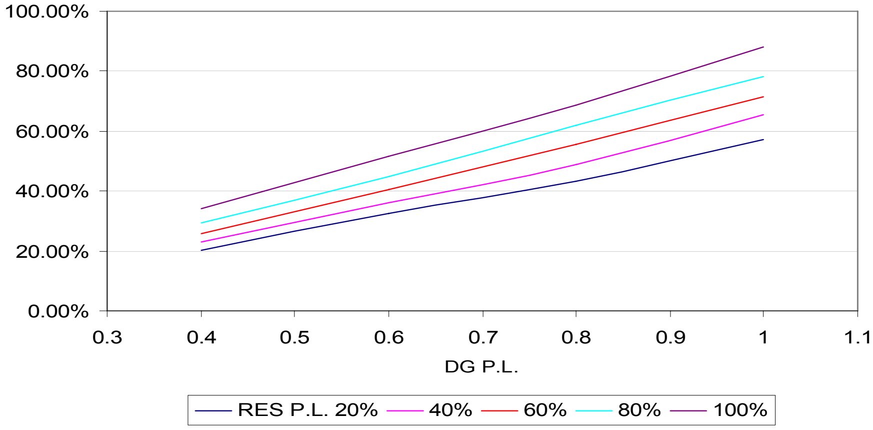

Figure A-3 Power Price Reduction (Original Value: 50.099€/MWh)

A.1.2 Environmental Mode

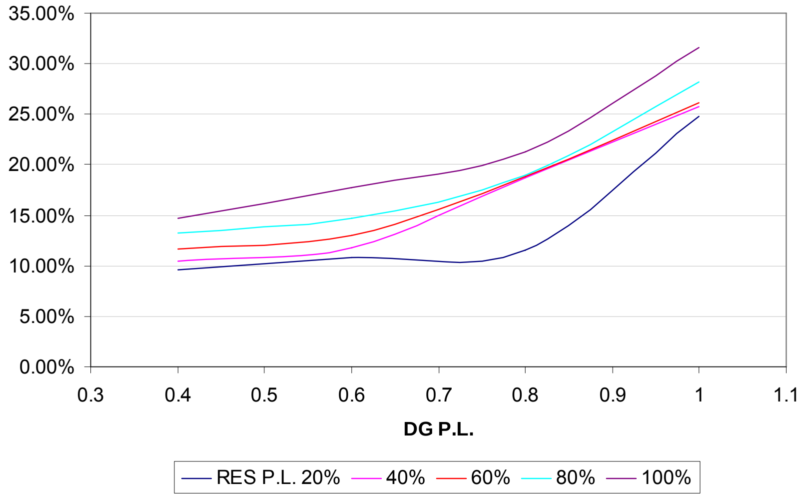

Figure A-4 Emission Cost Reduction (Original Value: 6€/kW)

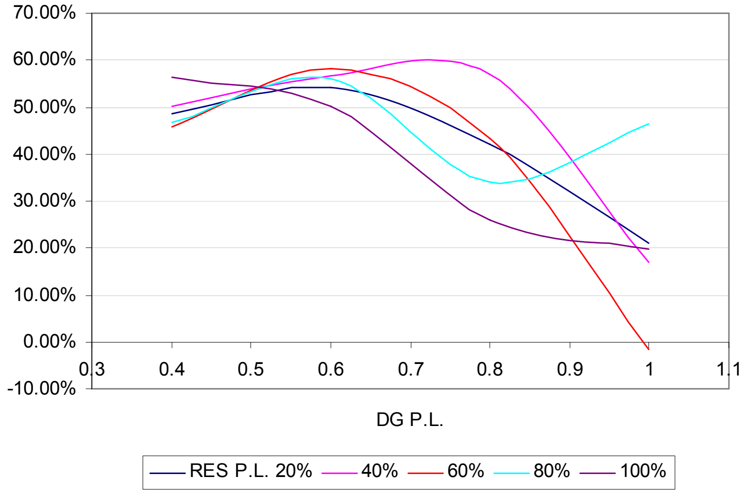

Figure A-5 Power Loss Improvement (Original Value: 12.09kW/hour)

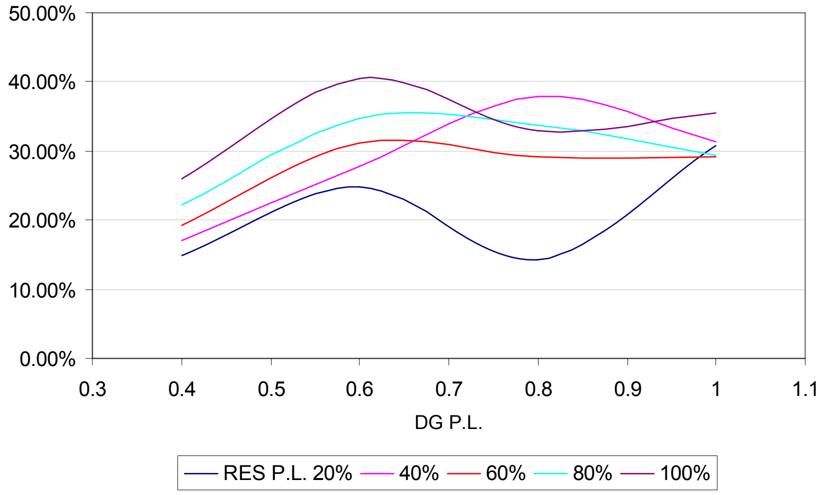

Figure A-6 Power Price Reduction (Original Value: 50.099€/MWh)

A.1.3 Technical Mode

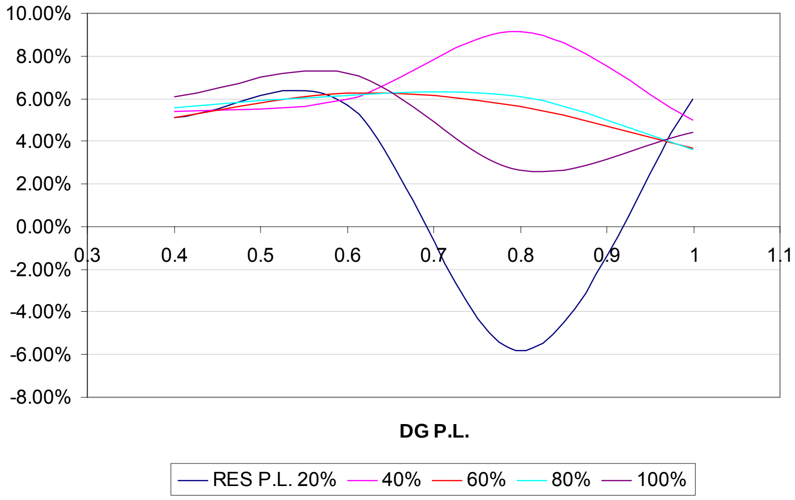

Figure A-7 Emission Cost Reduction (Original Value: 6€/kW)

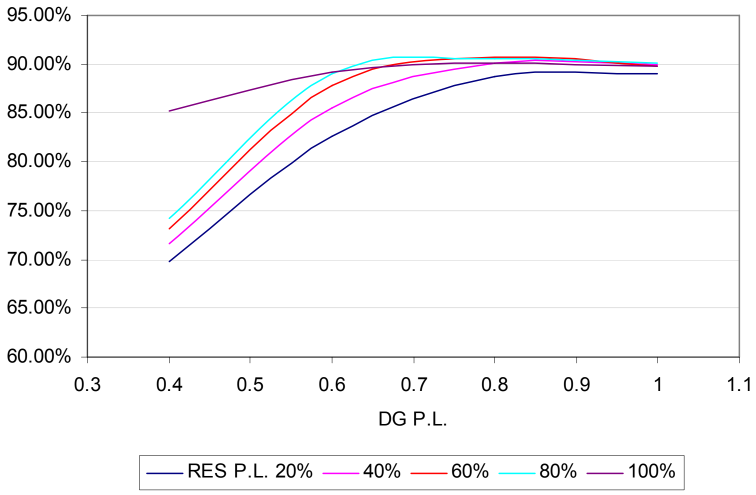

Figure A-8 Power Loss Improvement (Original Value: 12.09kW/hour)

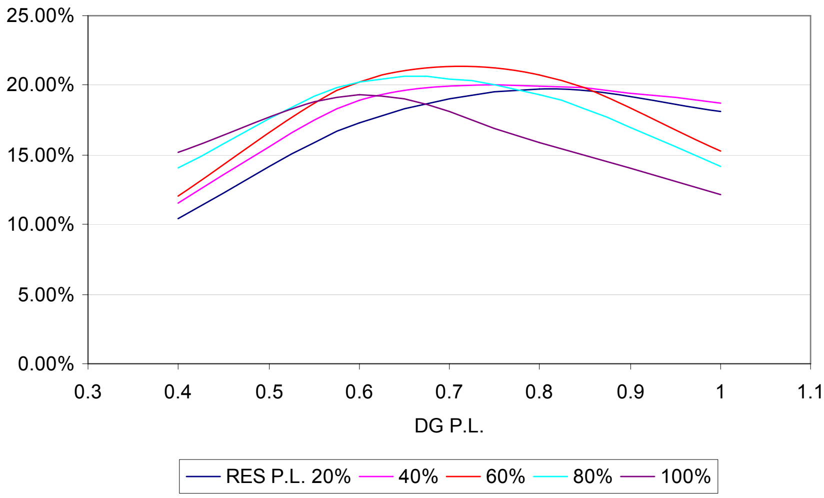

Figure A-9 Power Price Reduction (Original Value: 50.099€/MWh)

A.2 Information about typical EU Microgrids

A.2.1 General Information

	Busbar	Transformer	Line	Load [kW]
GR	17	1	15	415
IT_U	31	1	29	294.5
IT_R	22	1	20	118.75
MA_R	66	1	64	535
NL_U	18	1	16	500
PL	22	1	20	150
UK_R	76	2	74	1409.4
UK_U	83	1	81	1409.4
PT_U	60	1	58	1200
PT_SU	39	1	37	1500
PT_R	133	1	131	250
DK	161	1	159	20665.9

Table A-1 General Information about EU Microgrids

A.2.2 Economic Data of DG units in EU Microgrids

All information listed in this section is utilized in Equation 1-1.

Pmax	Maximum active power generation of DG [kW]
Pmin	Minimum active power generation of DG [kW]
Qmax	Maximum reactive power generation of DG [kVar]
Qmin	Minimum reactive power generation of DG [kVar]
a0	Constant coefficient of generation cost function
a1	First-order coefficient of generation cost function
a2	Second-order coefficient of generation cost function
EmiCost	First-order coefficient of emission cost function

Table A-2 Variant Index

DG	DG1	DG2	DG3	DG4	DG5	DG6
Pmax	40	30	30	82	80	62
Pmin	8	6	6	16.4	16	12.4
Qmax	20	15	15	41	40	31
Qmin	-20	-15	-15	-41	-40	-31
a0	401.5287	301.1465	301.1465	742.8281	742.8281	572.1784
a1	22.77069	24.77069	24.77069	23.03789	22.53789	22.78216
a2	0.004777	0.00637	0.00637	0.002209	0.002209	0.003026
EmiCost	5	4.75	4.75	6	6	5.5

Table A-3 DG Information for GR in Scenario 1

DG	DG1	DG2	DG3	DG4	DG5
Pmax	40	30	30	80	63
Pmin	8	6	6	16	12.6
Qmax	20	15	15	40	31.5

Qmin	-20	-15	-15	-40	-31.5
a0	401.5287	301.1465	301.1465	742.8281	572.1784
a1	22.77069	24.77069	24.77069	22.53789	22.28216
a2	0.004777	0.00637	0.00637	0.002209	0.003026
EmiCost	5	4.75	4.75	6	5.5

Table A-4 DG Information for GK in Scenario 2

DG	DG1	DG2
Pmax	30	30
Pmin	8	6
Qmax	20	15
Qmin	-20	-15
a0	301.1465	301.1465
a1	24.77069	24.77069
a2	0.00637	0.00637
EmiCost	4.75	4.75

Table A-5 DG Information for IT_R in Scenario 2

DG	DG1	DG2	DG3	DG4	DG5	DG6	DG7
Pmax	30	30	60	30	40	50	30
Pmin	6	6	12	6	8	10	6
Qmax	15	15	30	15	20	25	15
Qmin	-15	-15	-30	-15	-20	-25	-15
a0	301.1465	301.1465	572.1784	301.1465	401.5287	476.8153	301.1465
a1	24.77069	24.77069	22.28216	24.77069	22.77069	22.28216	24.77069
a2	0.00637	0.00637	0.003026	0.00637	0.004777	0.003631	0.00637
EmiCost	4.75	4.75	5.5	4.75	5	5.25	4.75

Table A-6 DG Information for MA_R in Scenario 2

DG	DG1	DG2	DG3
Pmax	100	60	40
Pmin	20	12	8
Qmax	50	30	20
Qmin	-50	-30	-20
a0	777.9619	572.1784	401.5287
a1	21.07229	22.28216	22.77069
a2	0.001481	0.003026	0.004777
EmiCost	6	5.5	5

Table A-7 DG Information for NL_U in Scenario 2

DG	DG1	DG2	DG3	DG4	DG5	DG6	DG7
Pmax	60	100	100	160	100	100	100
Pmin	12	20	20	32	20	20	20
Qmax	30	50	50	80	50	50	50
Qmin	-30	-50	-50	-80	-50	-50	-50
a0	451.7198	752.8663	752.8663	1204.586	752.8663	752.8663	752.8663
a1	50.32802	47.32802	47.32802	43.32802	47.32802	47.32802	47.32802

a2	0.002389	0.001433	0.001433	0.000896	0.001433	0.001433	0.001433
EmiCost	5	5.5	5.5	6.25	5.5	5.5	5.5

Table A-8 DG Information for PT_U in Scenario 2

DG	DG1	DG2	DG3	DG4	DG5	DG6	DG7
Pmax	120	120	120	120	150	120	150
Pmin	24	24	24	24	30	24	30
Qmax	60	60	60	60	75	60	75
Qmin	-60	-60	-60	-60	-75	-60	-75
a0	903.4396	903.4396	903.4396	903.4396	1204.586	903.4396	1204.586
a1	44.82802	44.82802	44.82802	44.82802	43.32802	44.82802	43.32802
a2	0.001194	0.001194	0.001194	0.001194	0.000896	0.001194	0.000896
EmiCost	6	6	6	6	6.25	6	6.25

Table A-9 DG Information for PT_SU in Scenario 2

DG	DG1	DG2	DG3	DG4
Pmax	30	30	30	30
Pmin	6	6	6	6
Qmax	15	15	15	15
Qmin	-15	-15	-15	-15
a0	225.8599	225.8599	225.8599	225.8599
a1	52.32802	52.32802	52.32802	52.32802
a2	0.004777	0.004777	0.004777	0.004777
EmiCost	4	4	4	4

Table A-10 DG Information for PT_R in Scenario 2

DG	DG1	DG2	DG3	DG4	DG5	DG6
Pmax	100	120	140	100	120	80
Pmin	20	24	28	20	24	16
Qmax	50	60	70	50	60	40
Qmin	-50	-60	-70	-50	-60	-40
a0	1505.733	1716.535	2037.758	1505.733	1716.535	1174.471
a1	44.65604	40.42324	38.16751	44.65604	40.42324	47.53964
a2	0.002866	0.002269	0.001979	0.002866	0.002269	0.003493
EmiCost	5.75	6.25	6.5	5.75	6.25	5

Table A-11 DG Information for UK_R in Scenario 2

DG	DG1	DG2	DG3	DG4	DG5	DG6
Pmax	100	120	110	120	150	100
Pmin	20	24	22	24	30	20
Qmax	50	60	55	60	75	50
Qmin	-50	-60	-55	-60	-75	-50
a0	1505.733	1716.535	1614.898	1716.535	2202.134	1505.733
a1	44.65604	40.42324	42.53964	40.42324	37.03964	44.65604
a2	0.002866	0.002269	0.002541	0.002269	0.001863	0.002866
EmiCost	5.75	6.25	6	6.25	6.75	5.75

Table A-12 DG Information for UK_U in Scenario 2

DG	DG1	DG2	DG3	DG4	DG5	DG6	DG7

Pmax	1500	2000	600	3000	3000	600	600
Pmin	300	400	120	600	600	120	120
Qmax	750	1000	300	1500	1500	300	300
Qmin	-750	-1000	-300	-1500	-1500	-300	-300
a0	22585.99	10038.22	3011.465	30114.65	30114.65	3011.465	3011.465
a1	14.65604	14.88535	24.88535	9.770694	9.770694	24.88535	24.88535
a2	0.000191	4.78E-05	0.000159	6.37E-05	6.37E-05	0.000159	0.000159
EmiCost	8	9	6	10	10	6	6

Table A-13 DG Information for DK in Scenario 2

DG	DG1	DG2	DG3	DG4	DG5	DG6	DG7	DG8	DG9	DG10
Pmax	55	162	85	85	55	55	80	80	130	55
Pmin	10	25	25	25	10	10	20	20	20	10
Qmax	27.5	81	42.5	42.5	27.5	27.5	40	40	65	27.5
Qmin	-27.5	-81	-42.5	-42.5	-27.5	-27.5	-40	-40	-65	-27.5
a0	1320	900	960	972	1330	1340	740	734	1360	1350
a1	51.84	39.4	55.48	55.48	54.54	55.58	44.52	44.52	33.2	57.12
a2	0.00826	0.00796	0.00158	0.00161	0.00444	0.00346	0.01424	0.001402	0.00422	0.00624
EmiCost	6.75	9	7.7	7.7	6.75	6.75	7.5	7.5	9	6.75

Table A-14 DG Information for DE in Scenario 2

A.3 Results for EU Microgrids

A.3.1 Economic Mode

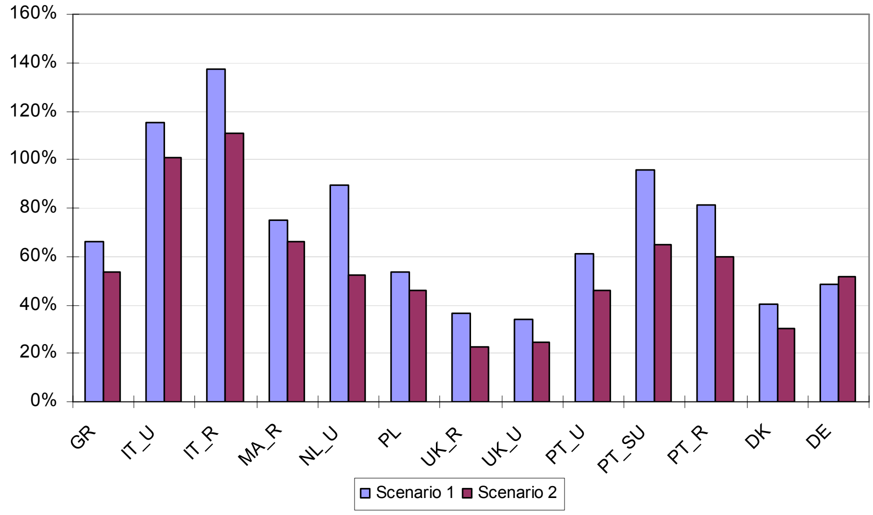

Figure A-10 Power Price Reduction

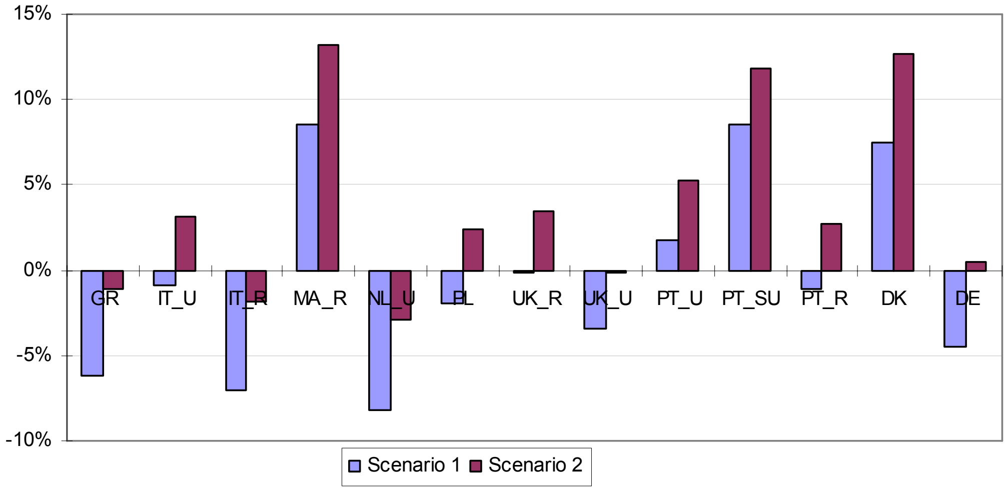

Figure A-11 Emission Cost Reduction

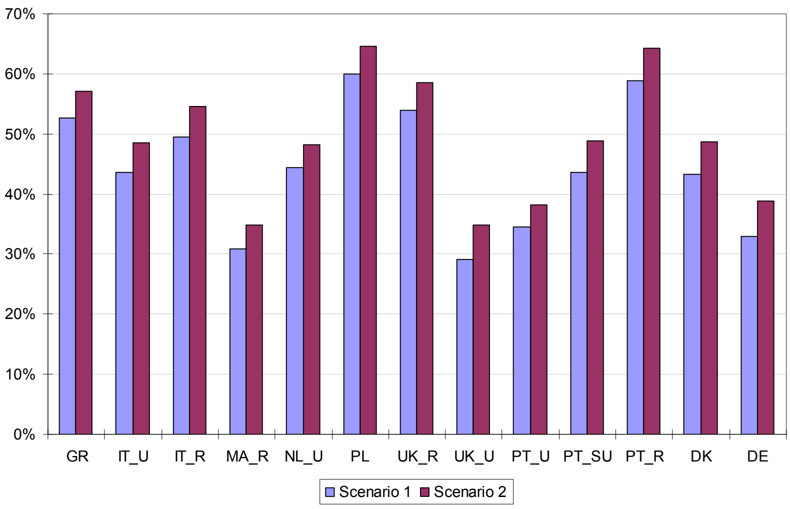

Figure A-12 Power Loss Improvement

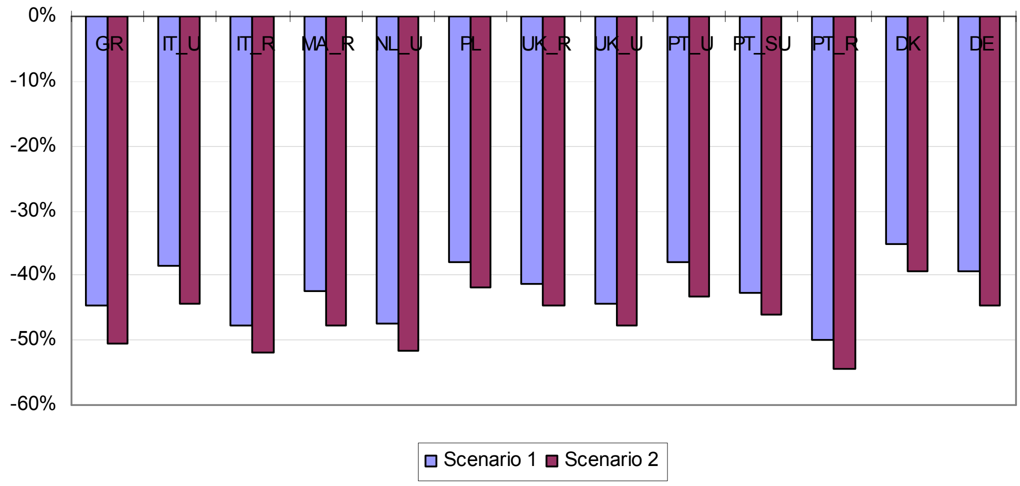

Figure A-13 Line Loading Reduction

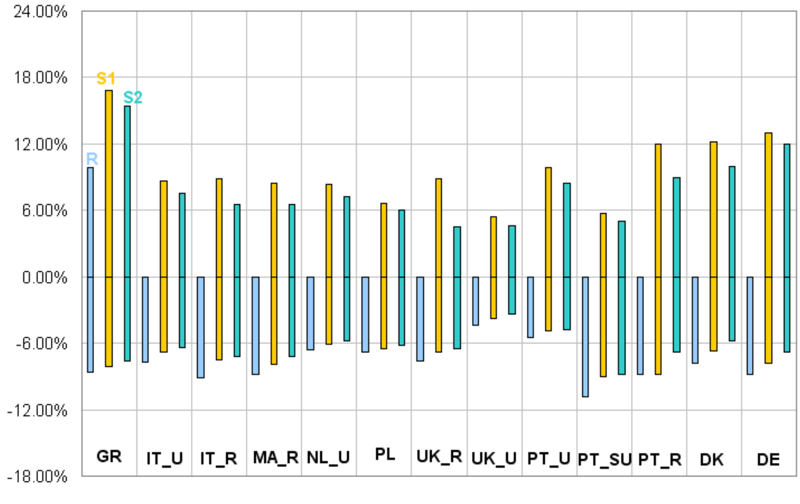

Figure A-14 Voltage Band

A.3.2 Environmental Mode

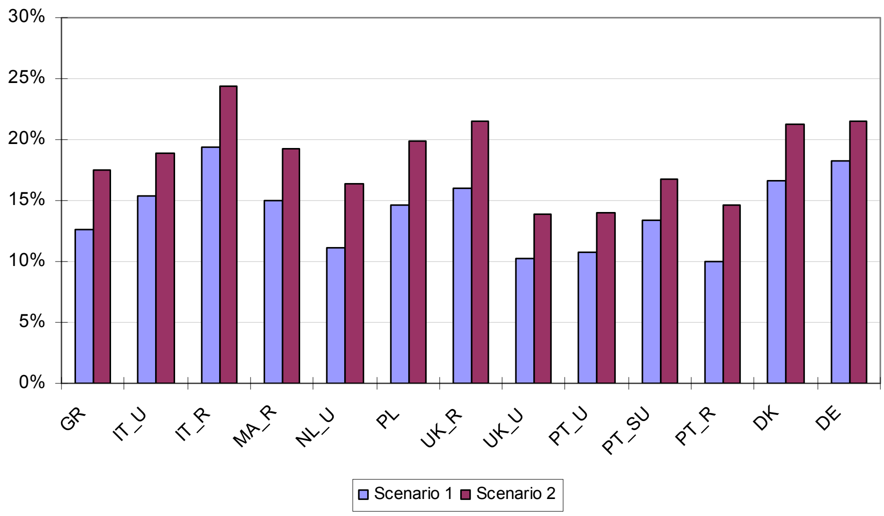

Figure A-15 Power Price Reduction

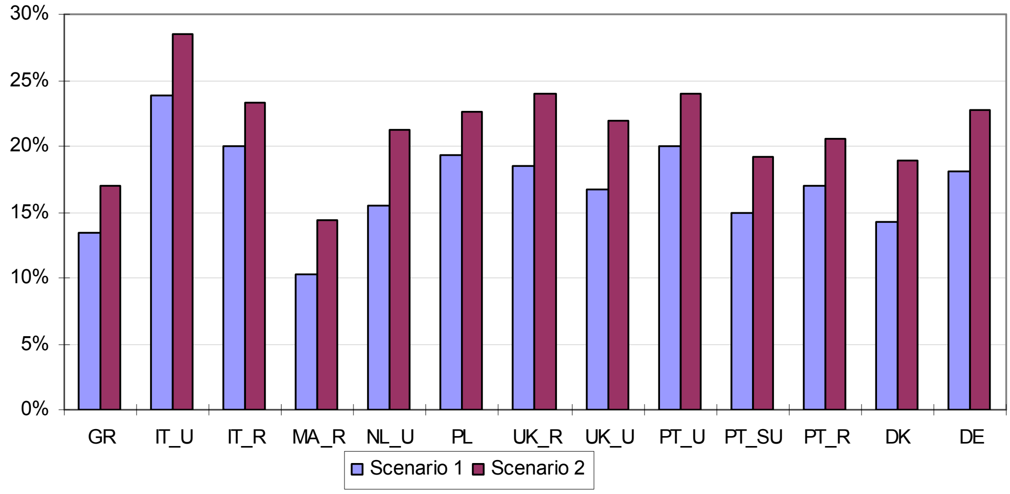

Figure A-16 Emission Cost Reduction

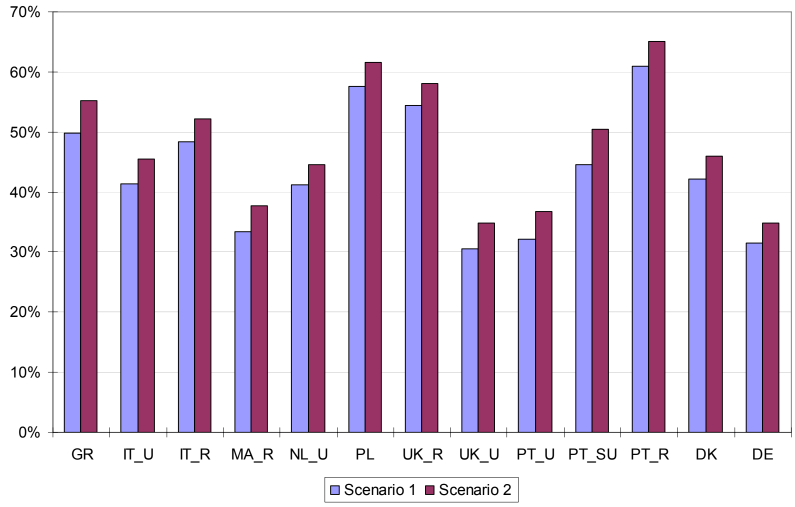

Figure A-17 Power Loss Improvement

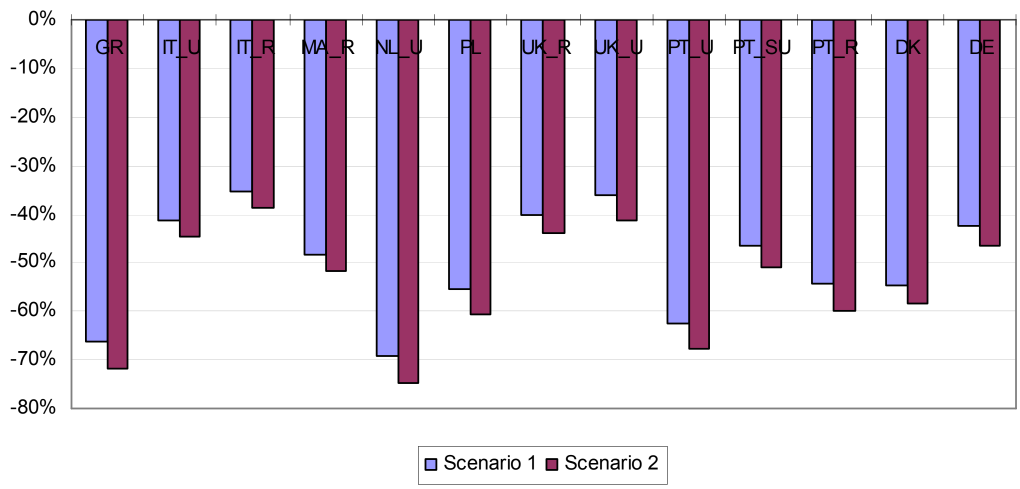

Figure A-18 Line Loading Reduction

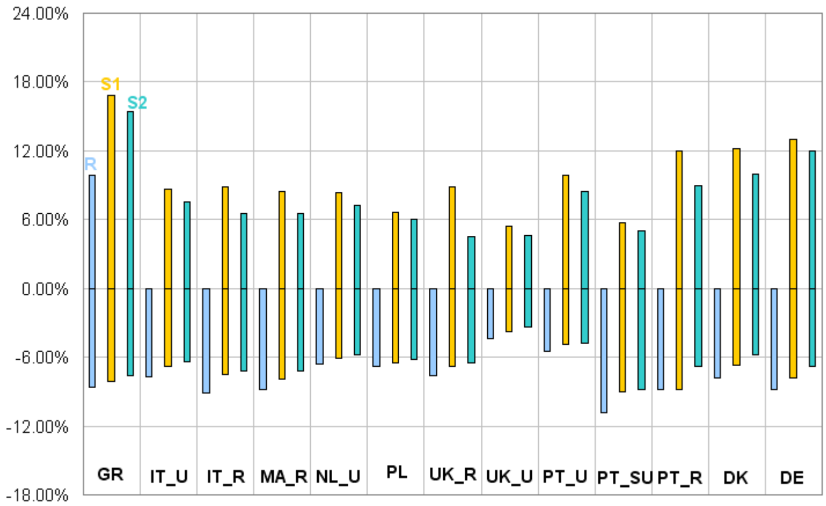

Figure A-19 Voltage Band

A.3.3 Technical Mode

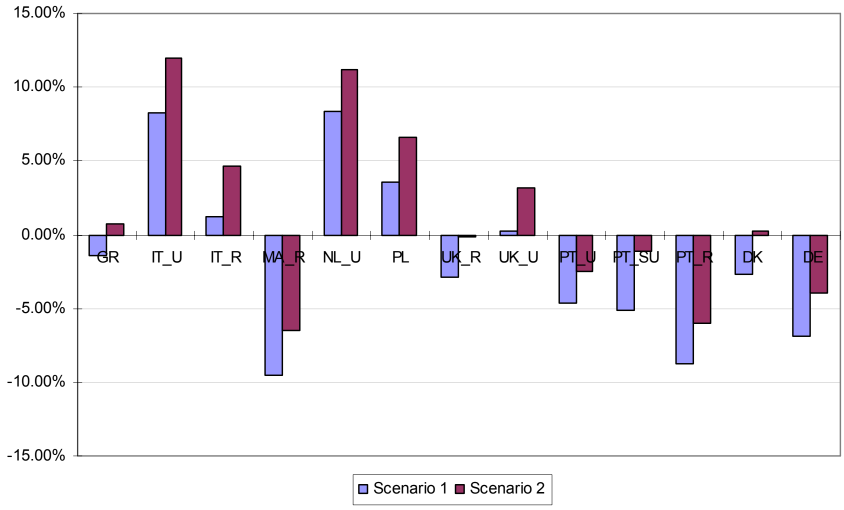

Figure A-20 Power Price Reduction

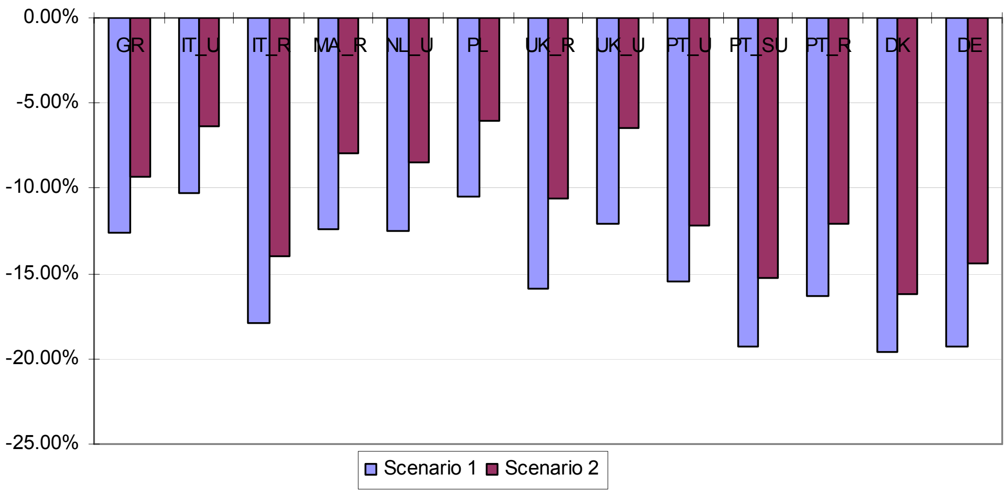

Figure A-21 Emission Cost Reduction

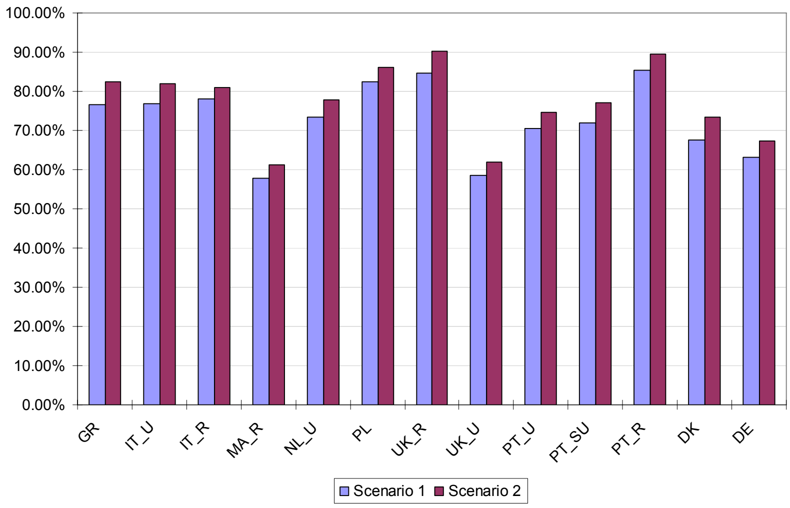

Figure A-22 Power Loss Improvement

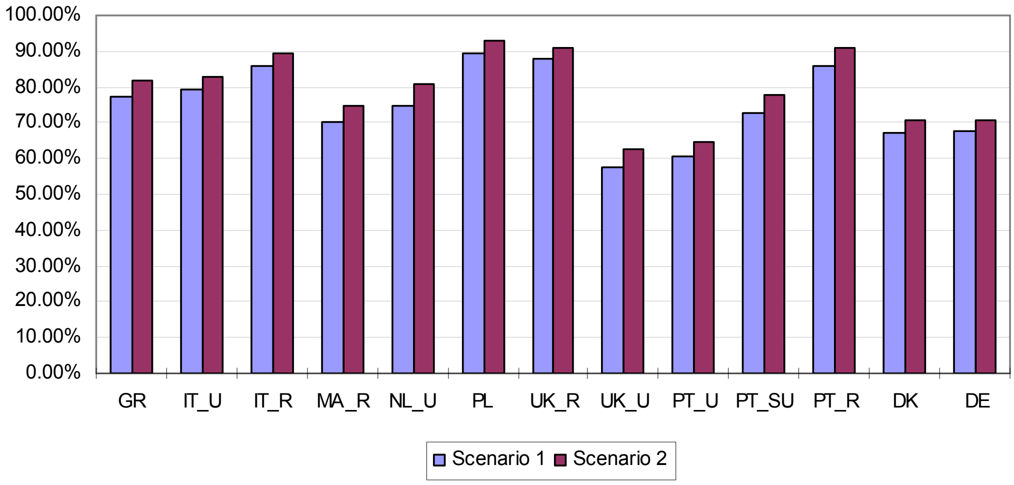

Figure A-23 Line Loading Reduction

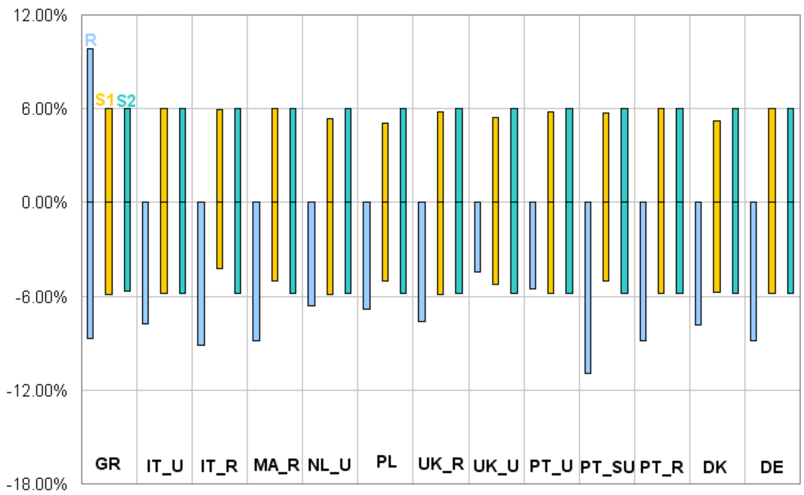

Figure A-24 Voltage Band

A.4 EU Microgrid Topologies

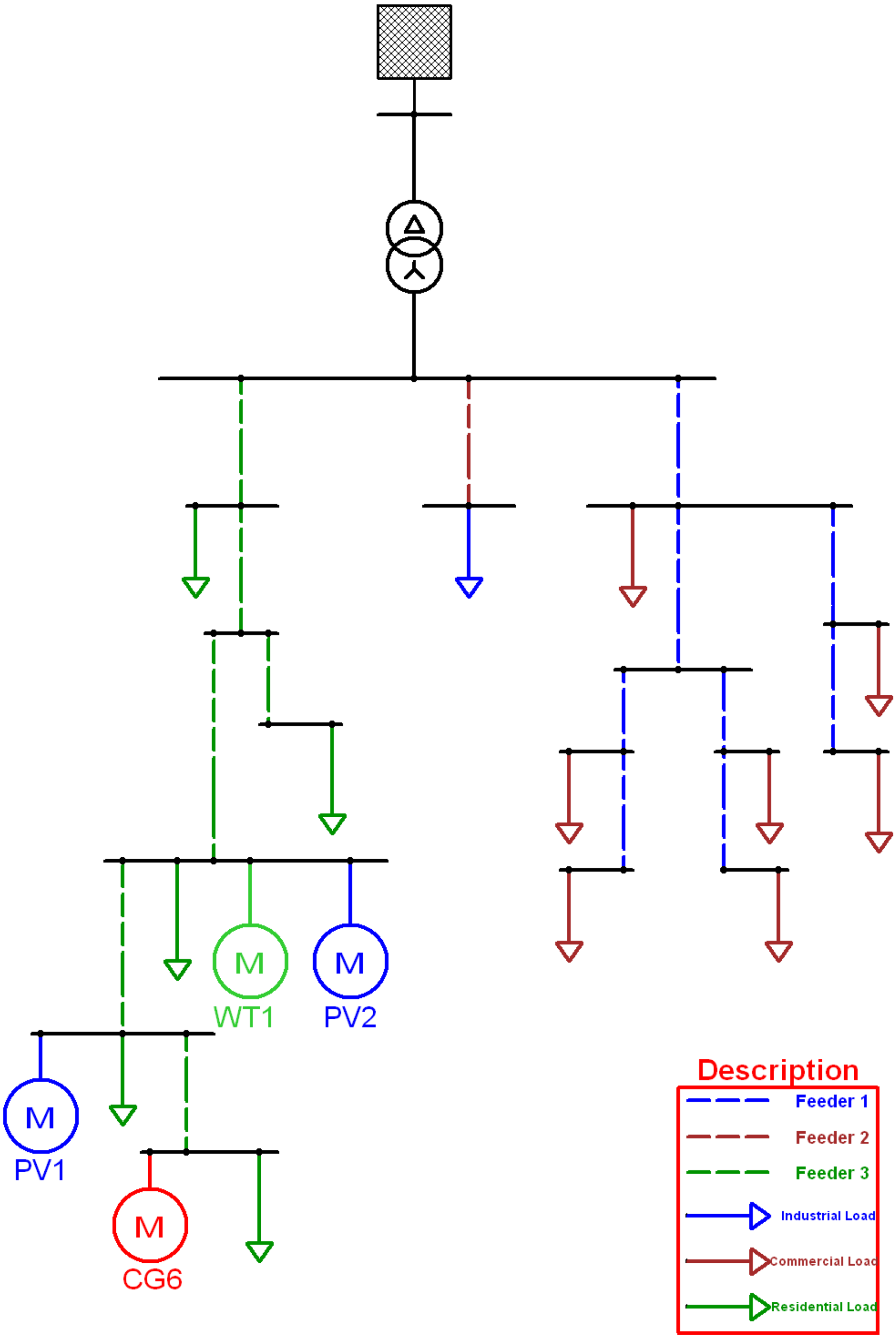

Figure A-25 Microgrid of Greece

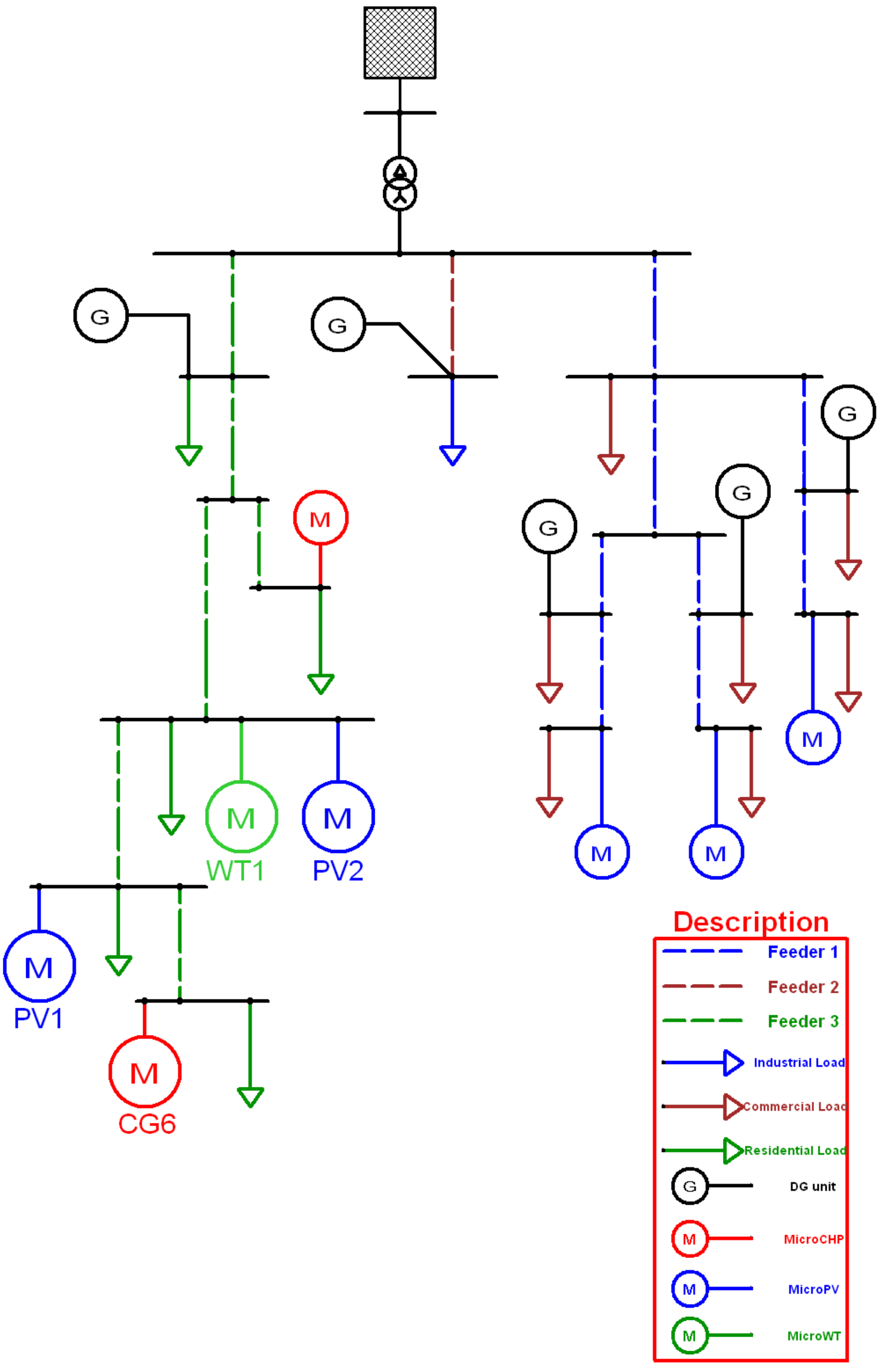

Figure A-26 Microgrid of Greece for Scenario 2

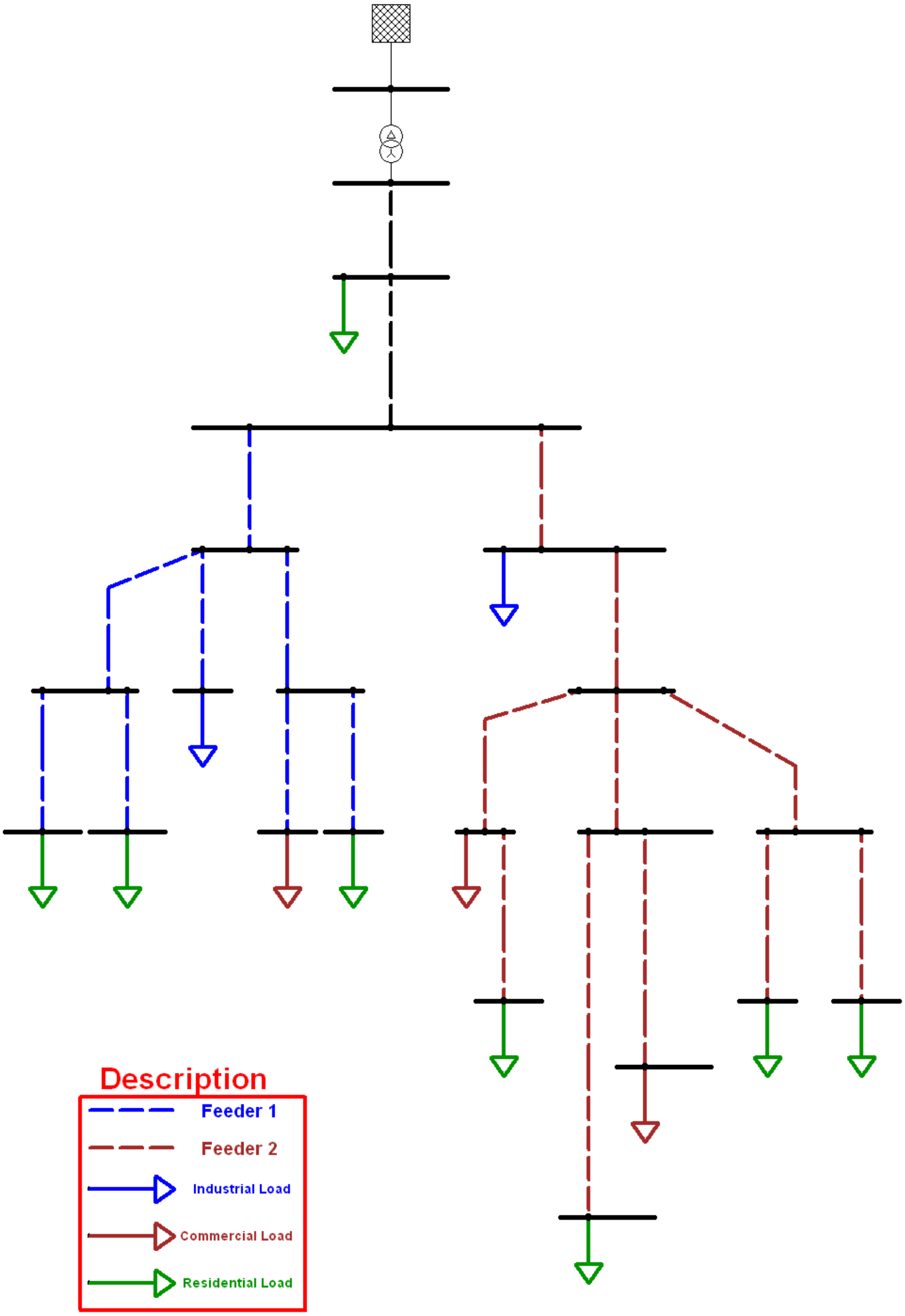

Figure A-27 Rural Microgrid of Italy

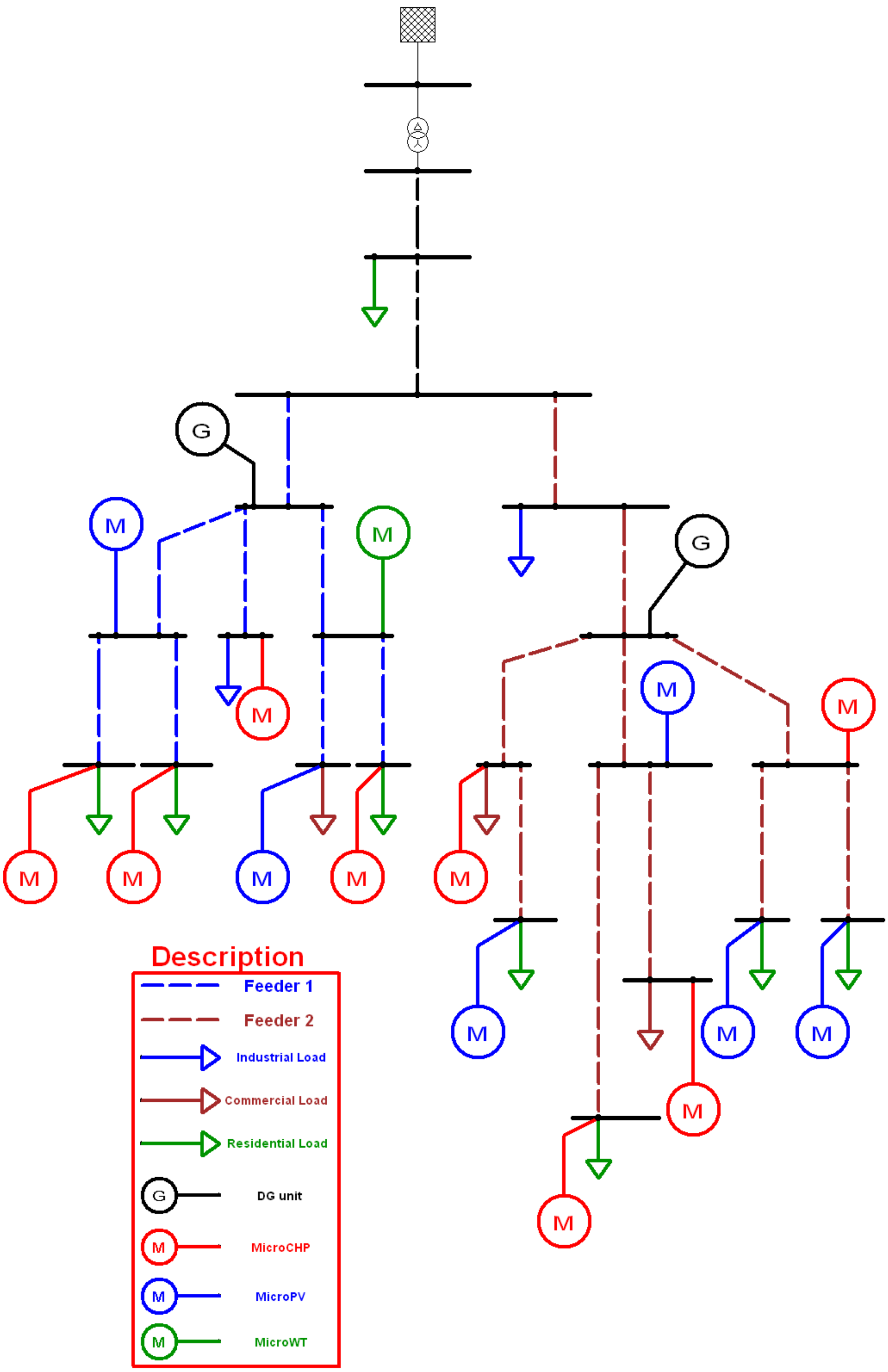

Figure A-28 Rural Microgrid of Italy for Scenario 2

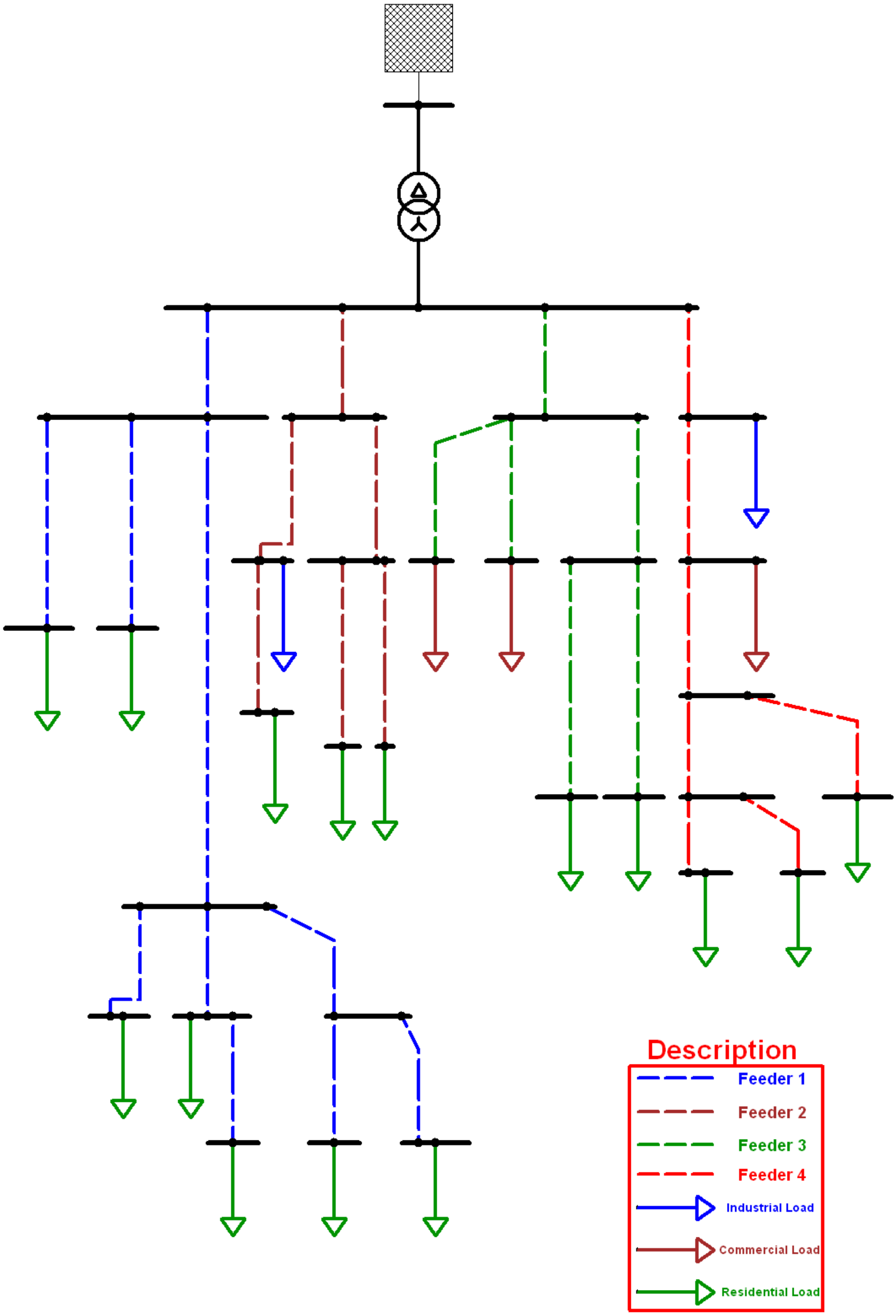

Figure A-29 Urban Microgrid of Italy

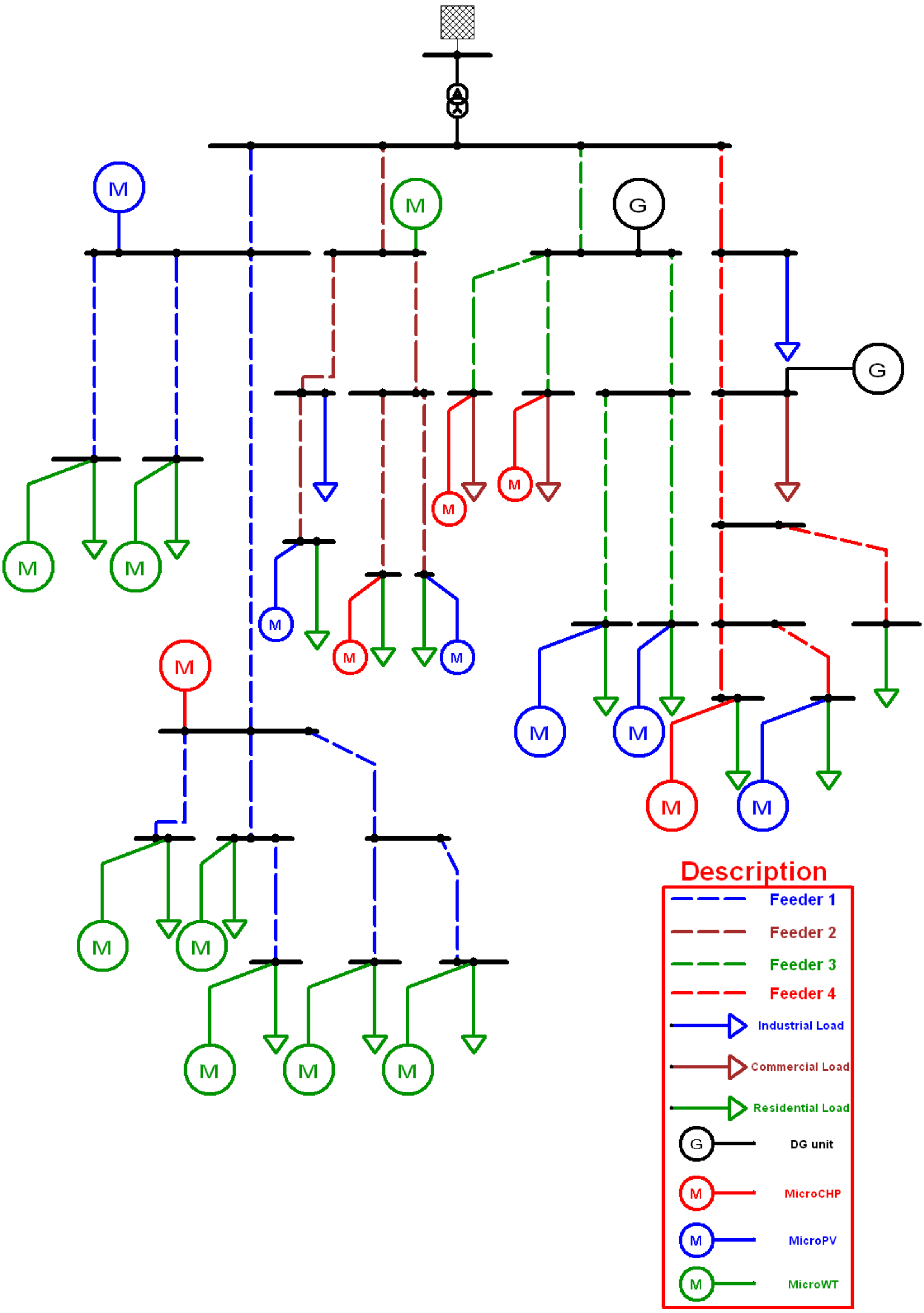

Figure A-30 Urban Microgrid of Italy for Scenario 2

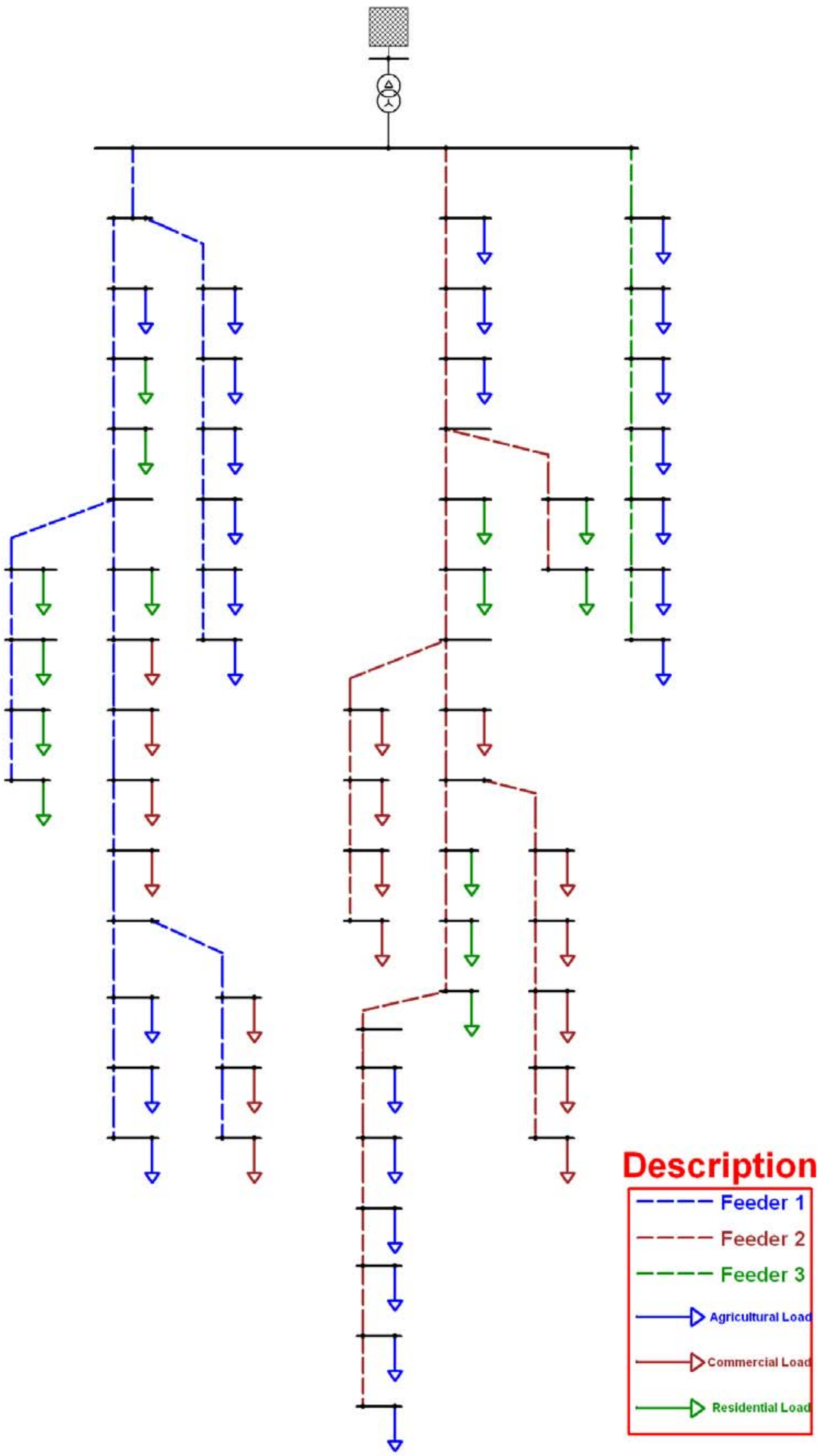

Figure A-31 Rural Microgrid of Macedonia

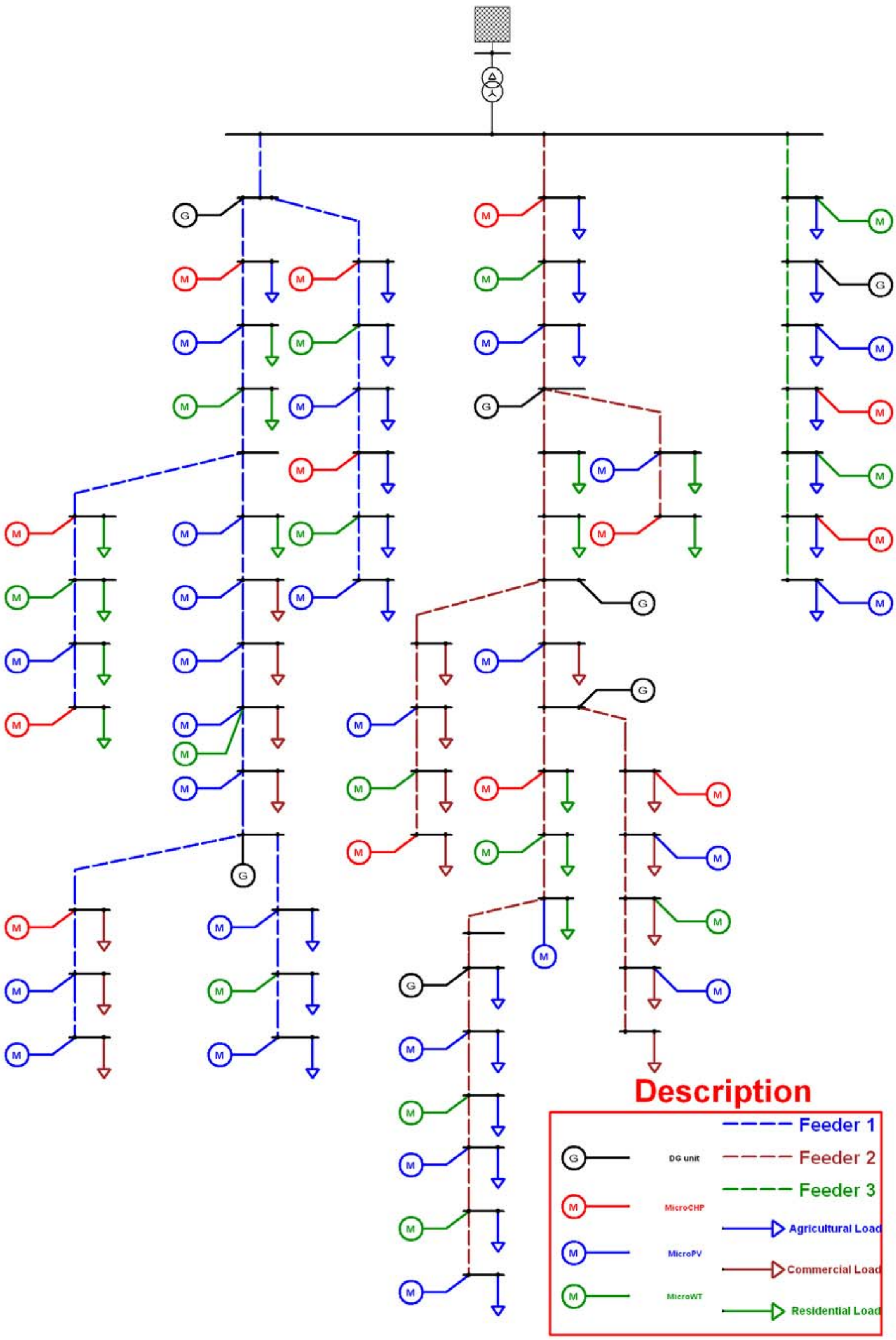

Figure A-32 Rural Microgrid of Macedonia for Scenario 2

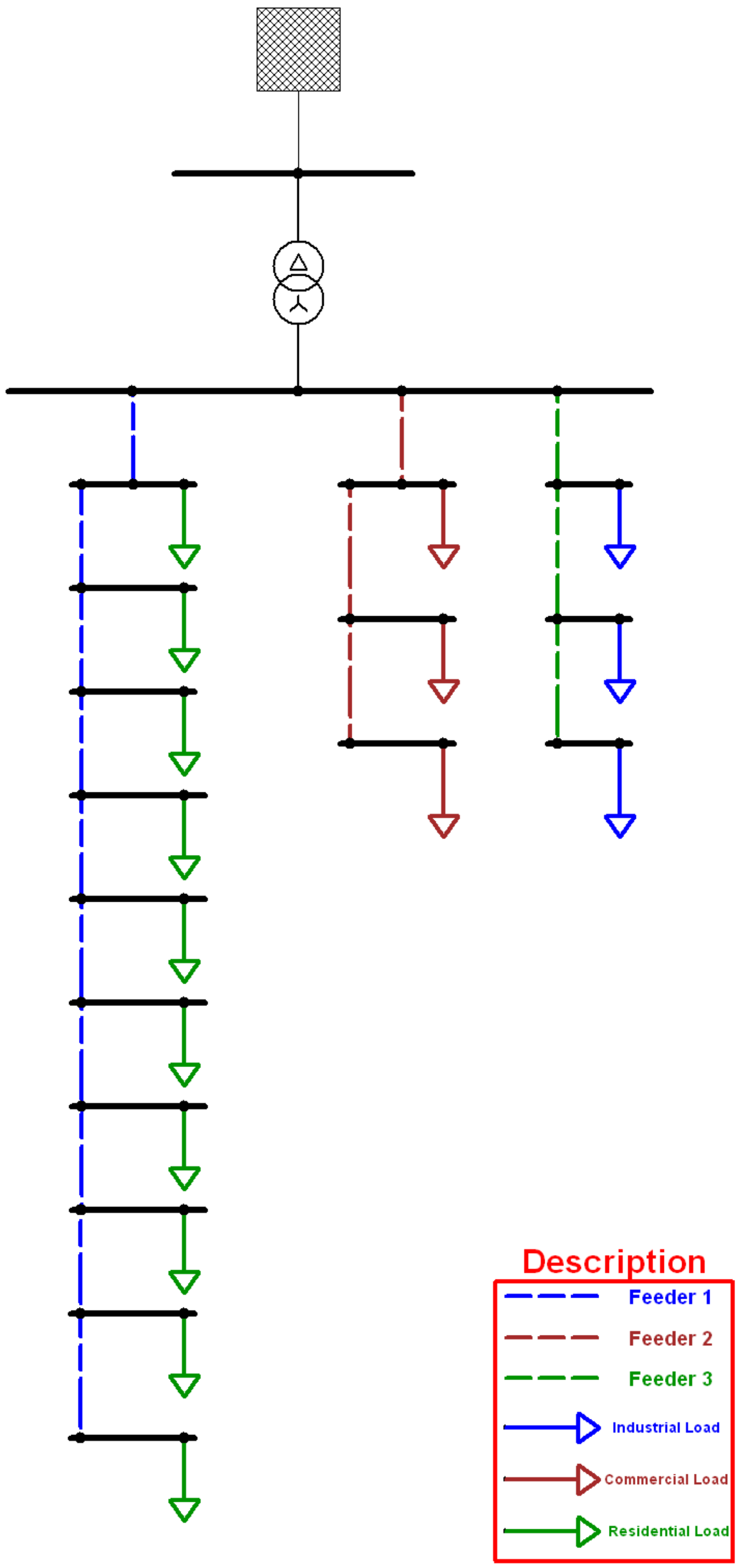

Figure A-33 Urban Microgrid of Netherland

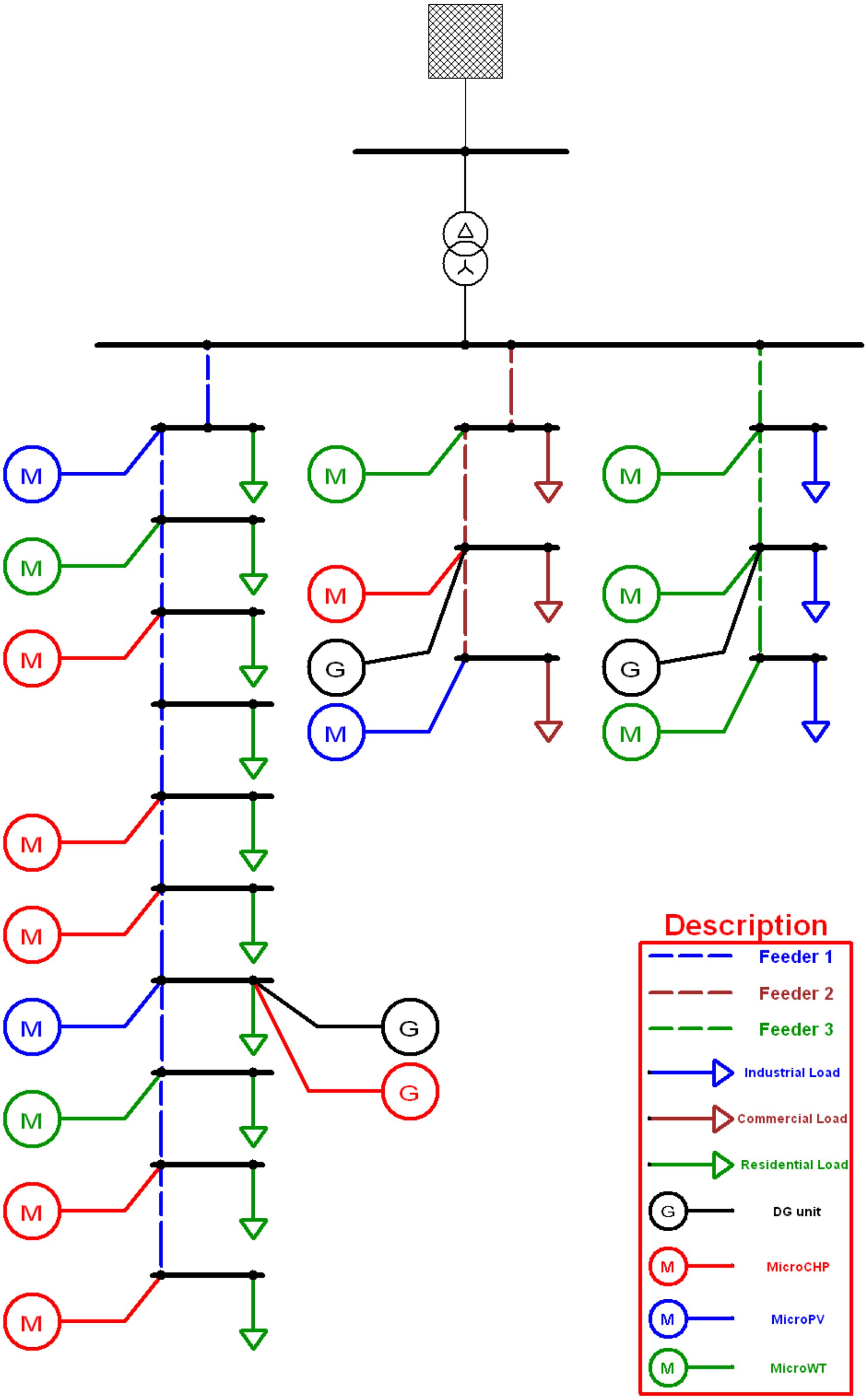

Figure A-34 Urban Microgrid of Netherland for Scenario 2

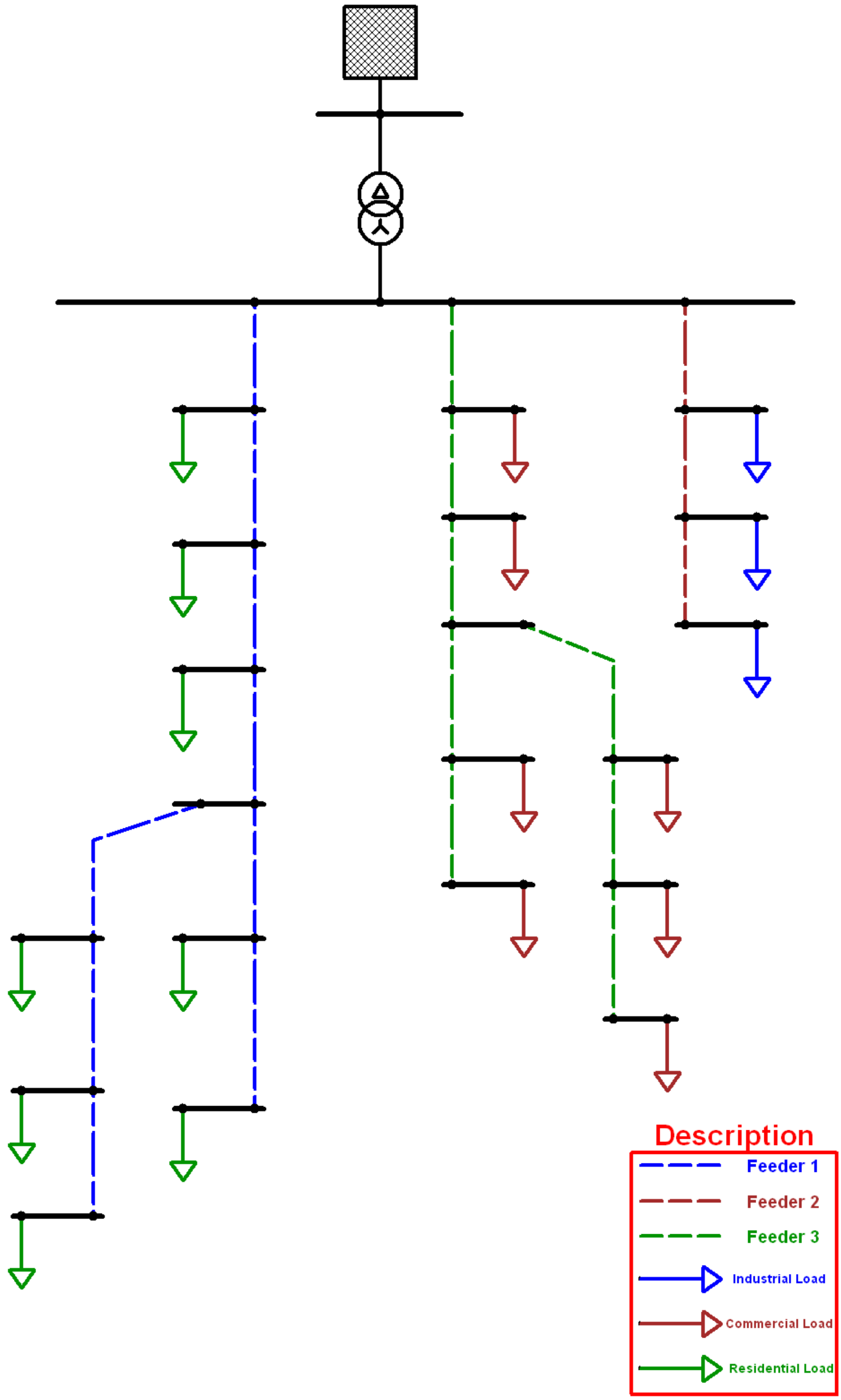

Figure A-35 Microgrid of Poland

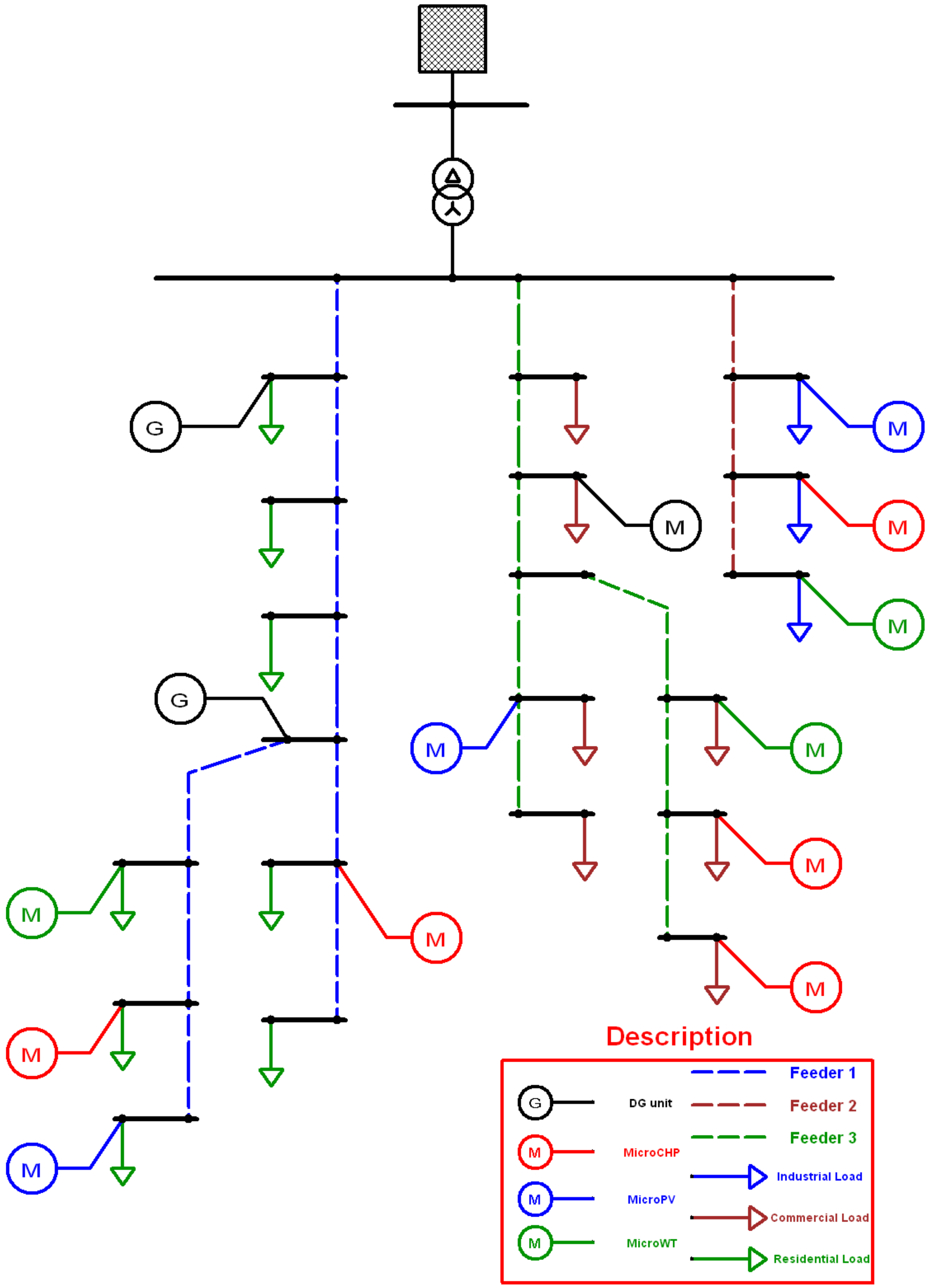

Figure A-36 Microgrid of Poland for Scenario

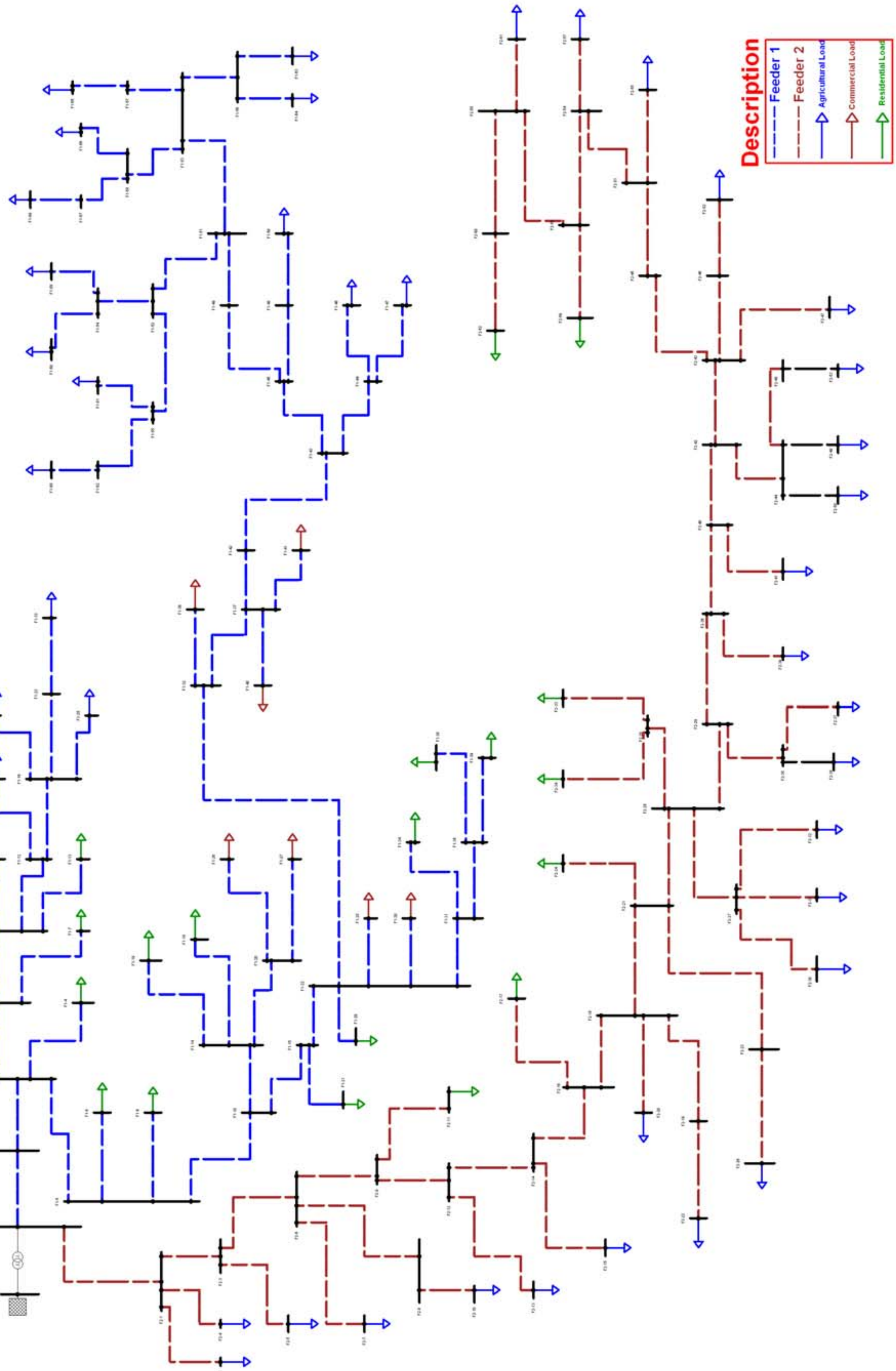

Figure A-37 Rural Microgrid of Portugal

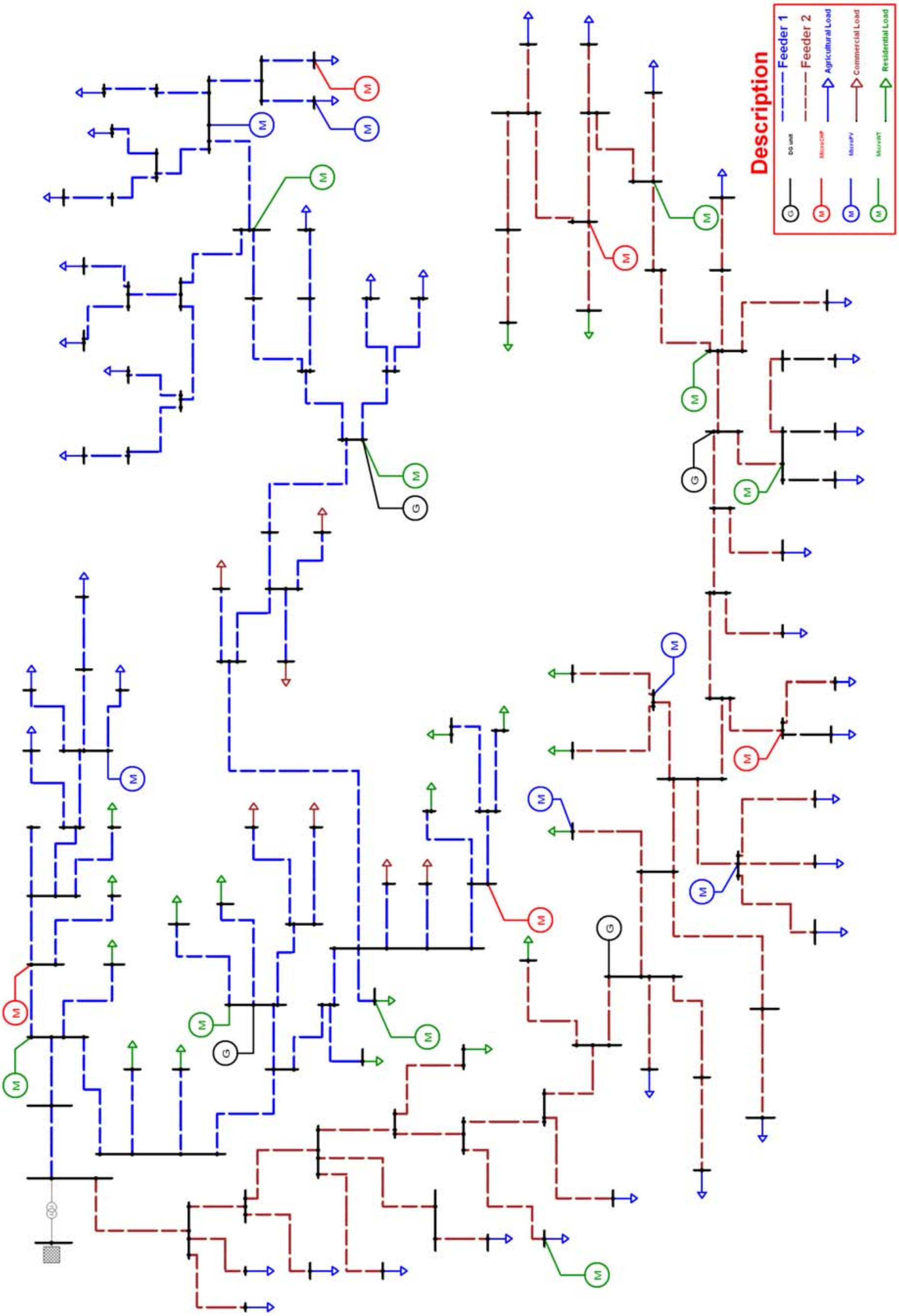

Figure A-38 Rural Microgrid of Portugal for Scenario 2

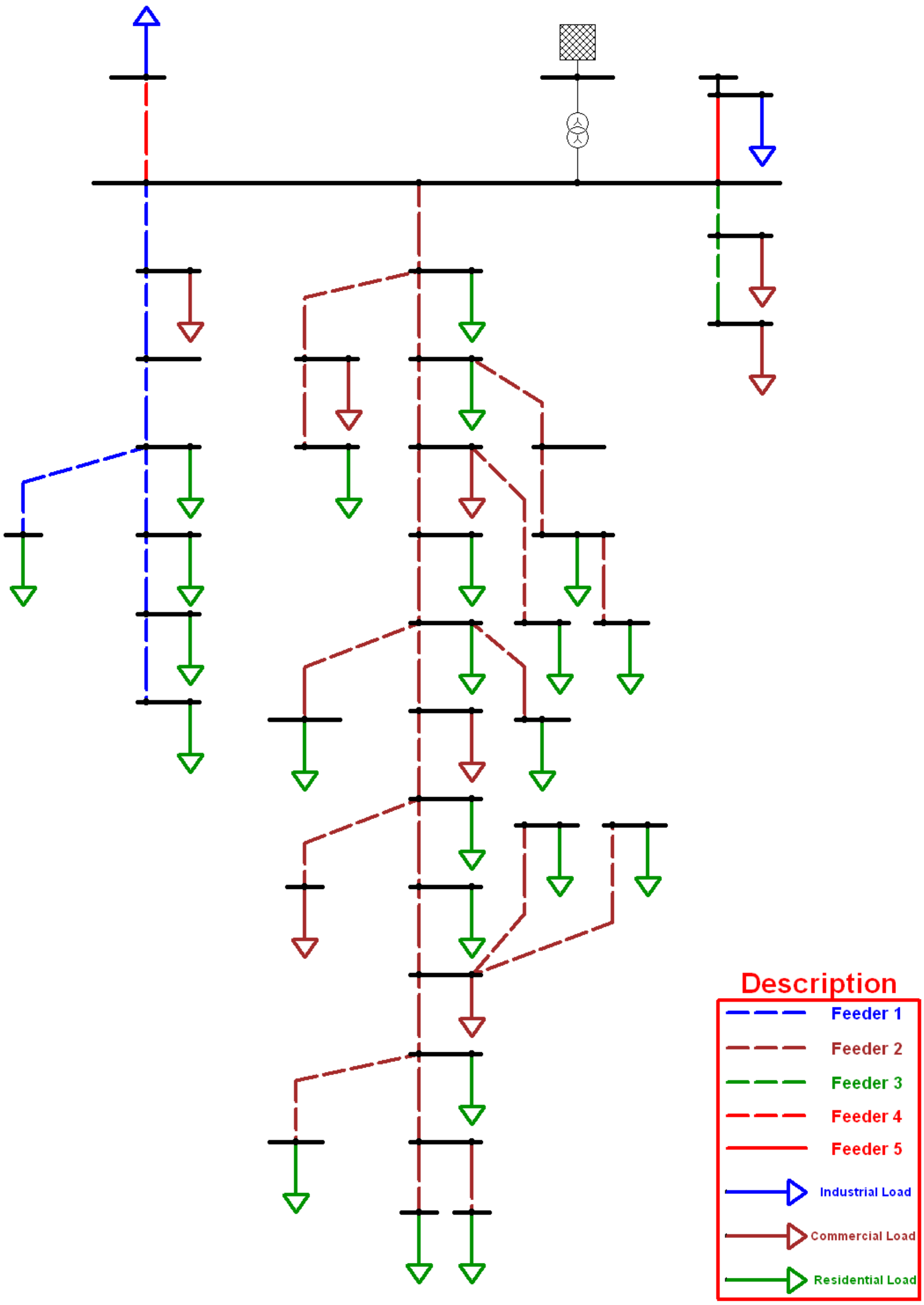

Figure A-39 Semi Urban Microgrid of Portugal

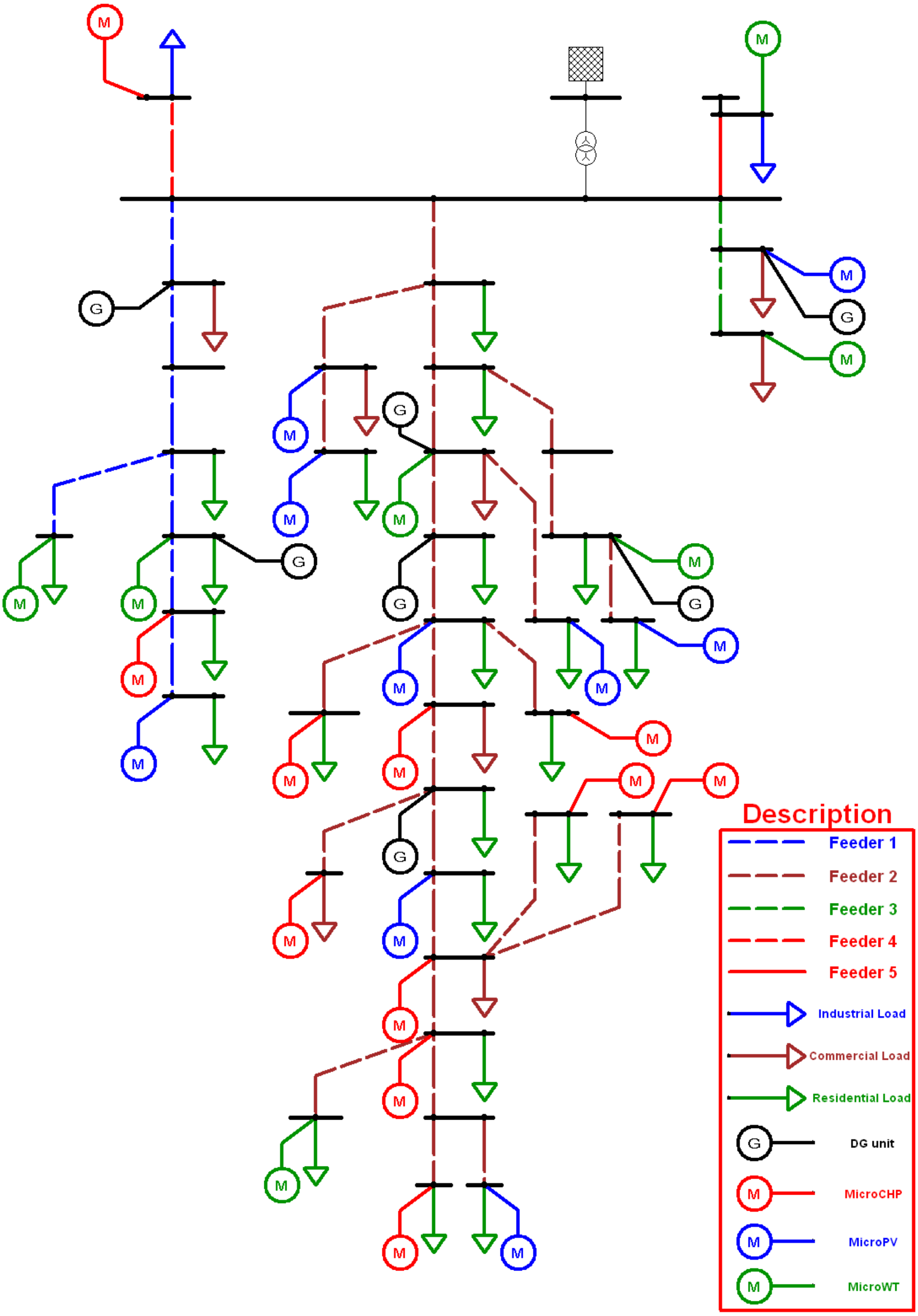

Figure A-40 Semi-Urban Microgrid of Portugal for Scenario 2

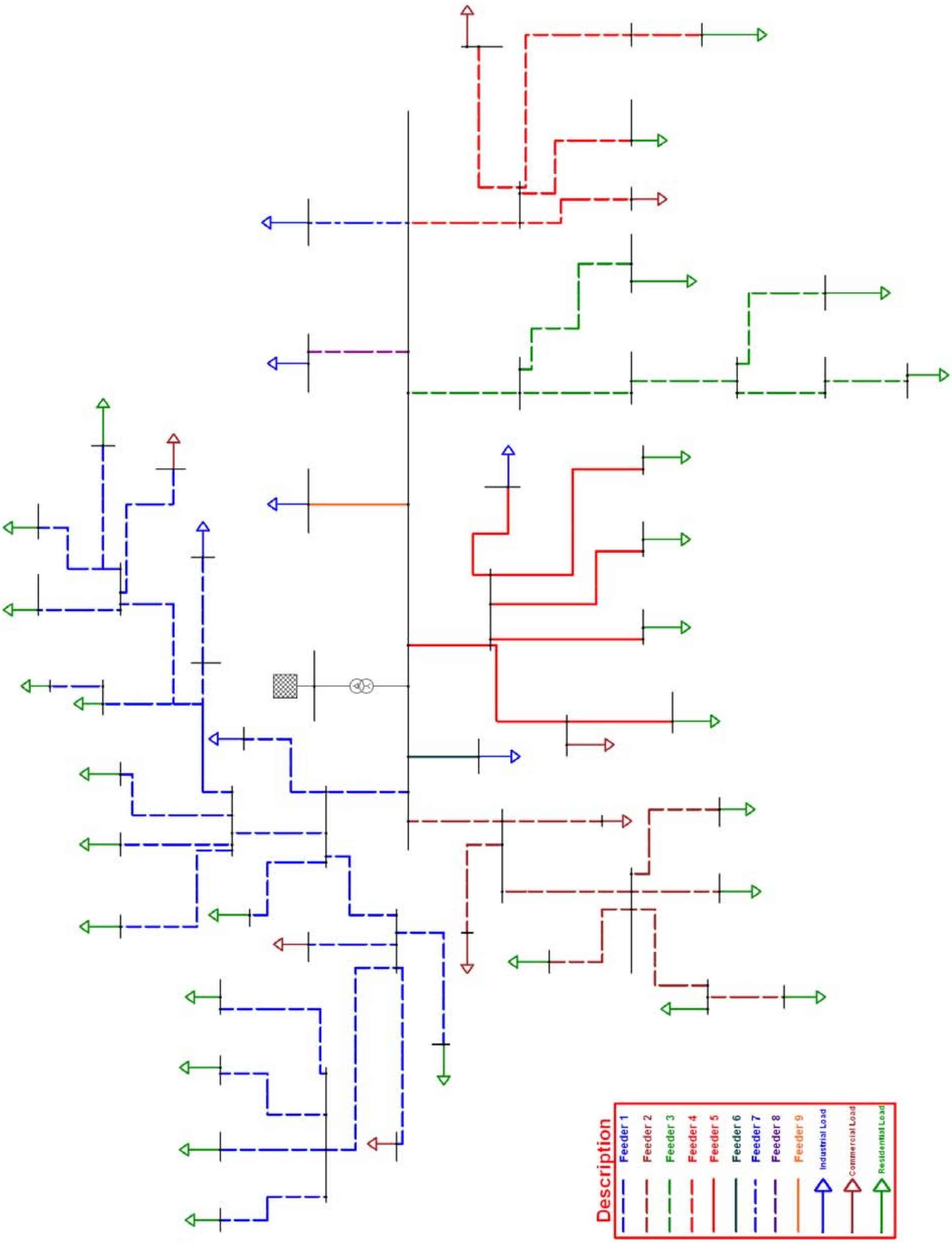

Figure A-41 Urban Microgrid of Portugal

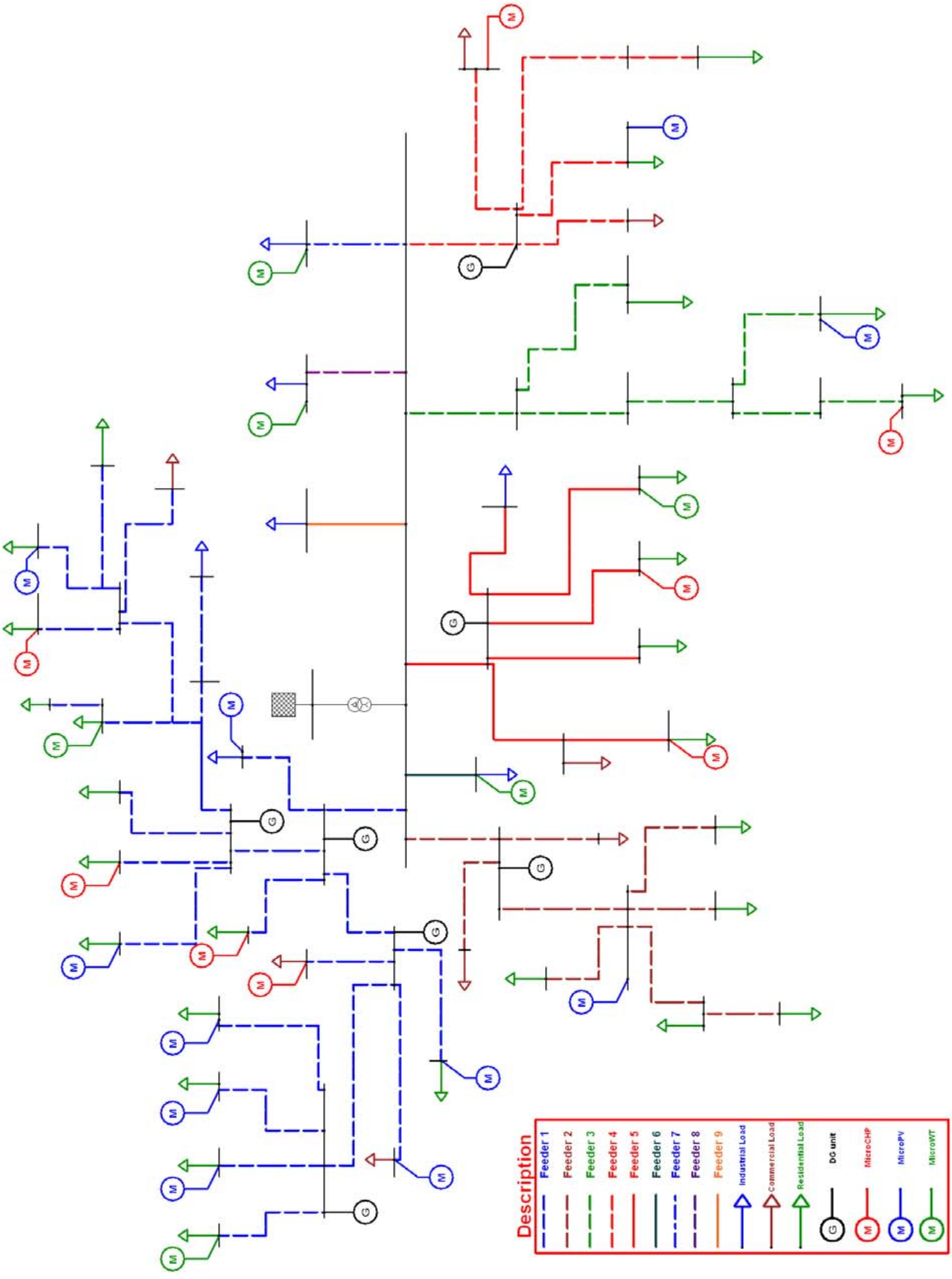

Figure A-42 Urban Microgrid of Portugal for Scenario 2

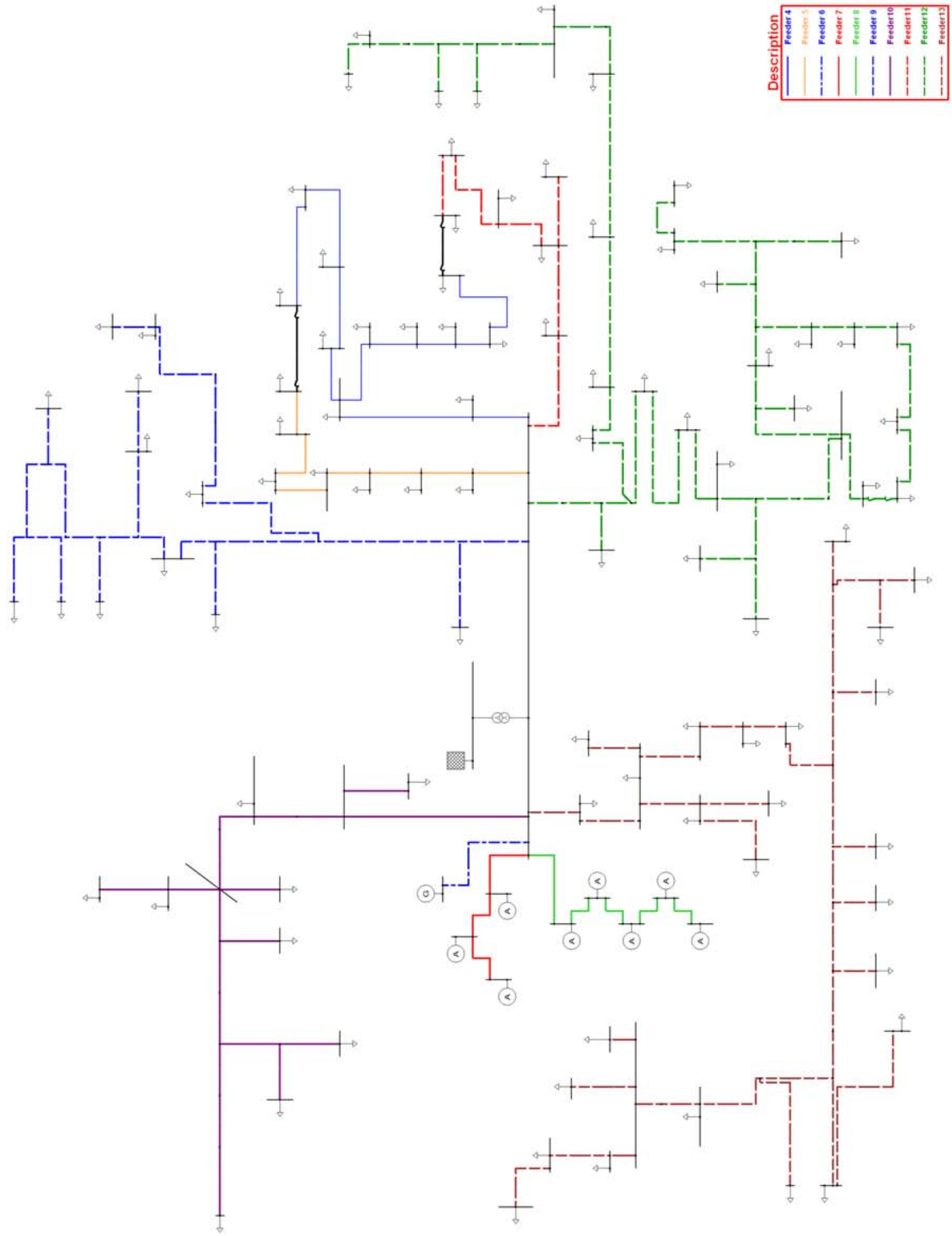

Figure A-43 Microgrid of Denmark3

[3] Allocation and sizing of RES units for *Scenario 2* are the same as for *Scenario 1*.

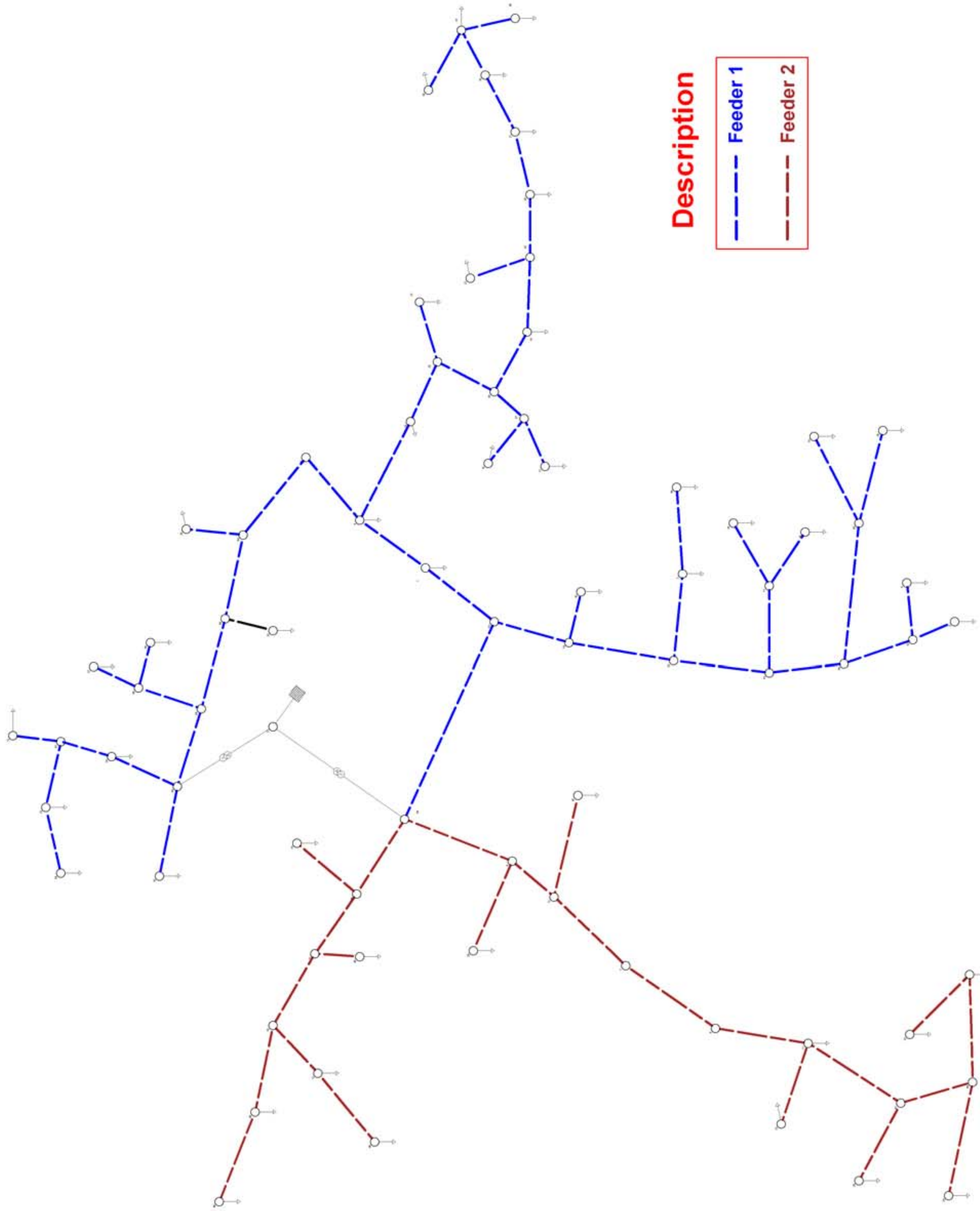

Figure A-44 Rural Microgrid of UK

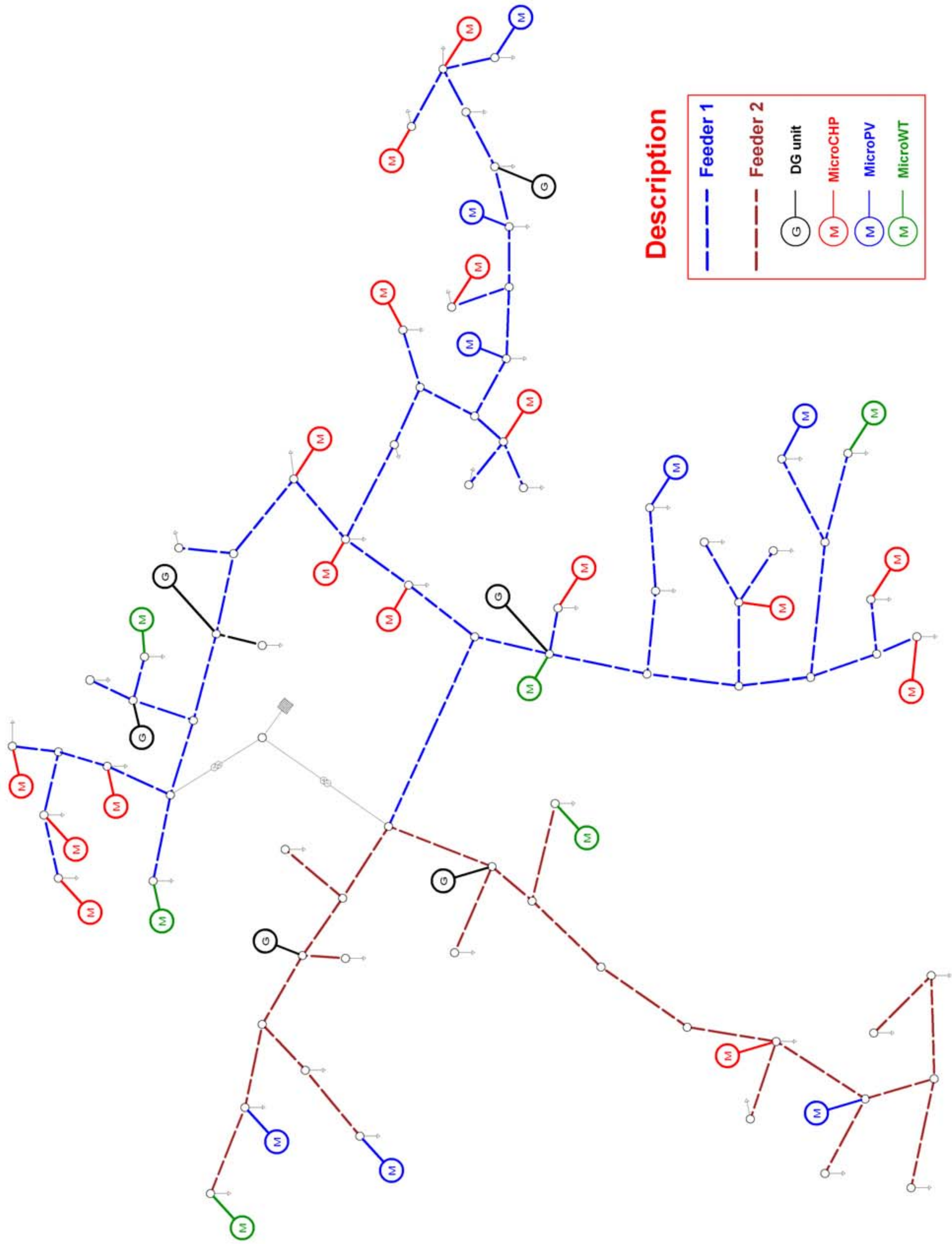

Figure A-45 Rural Microgrid of UK for Scenario 2

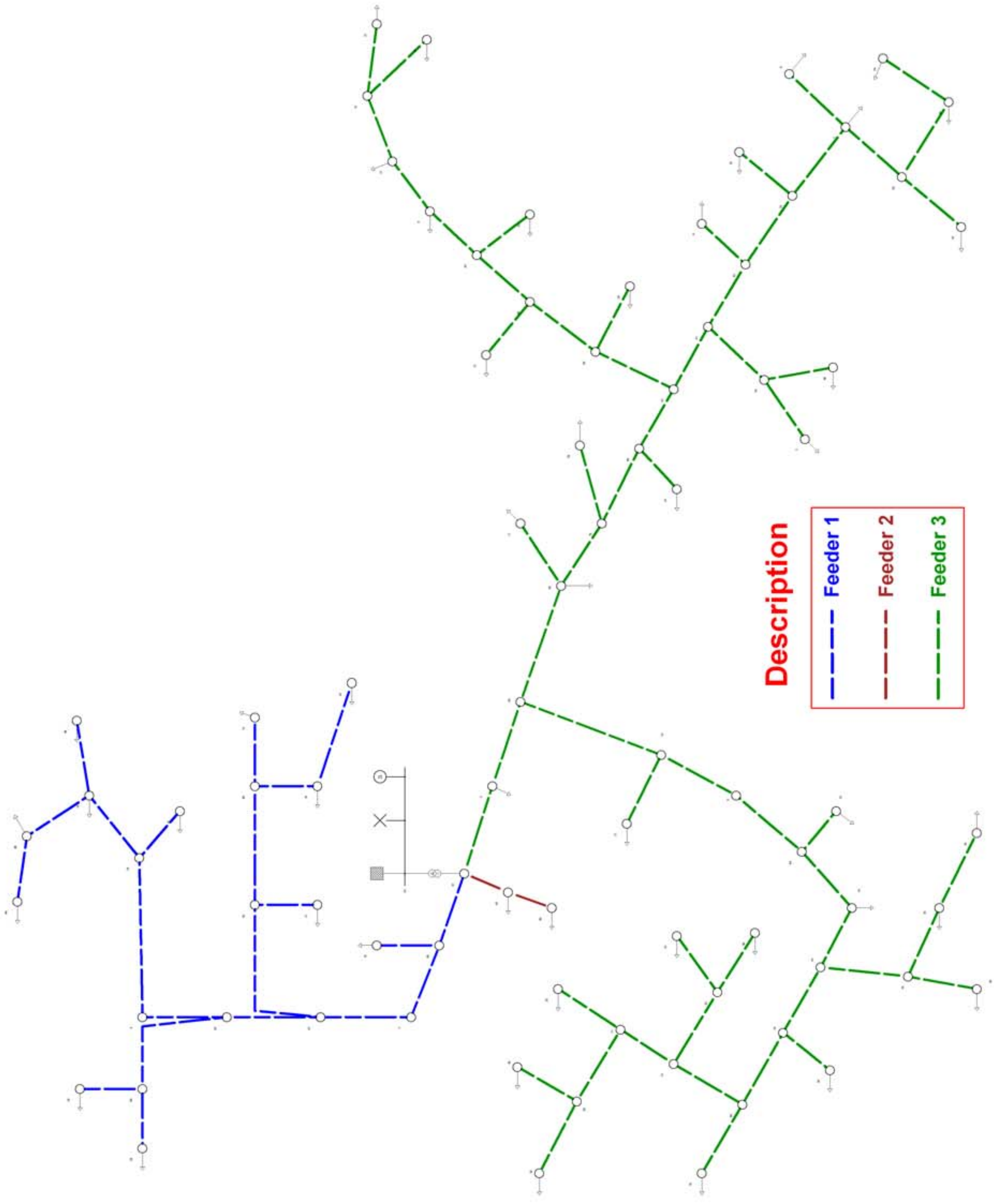

Figure A-46 Urban Microgrid of UK

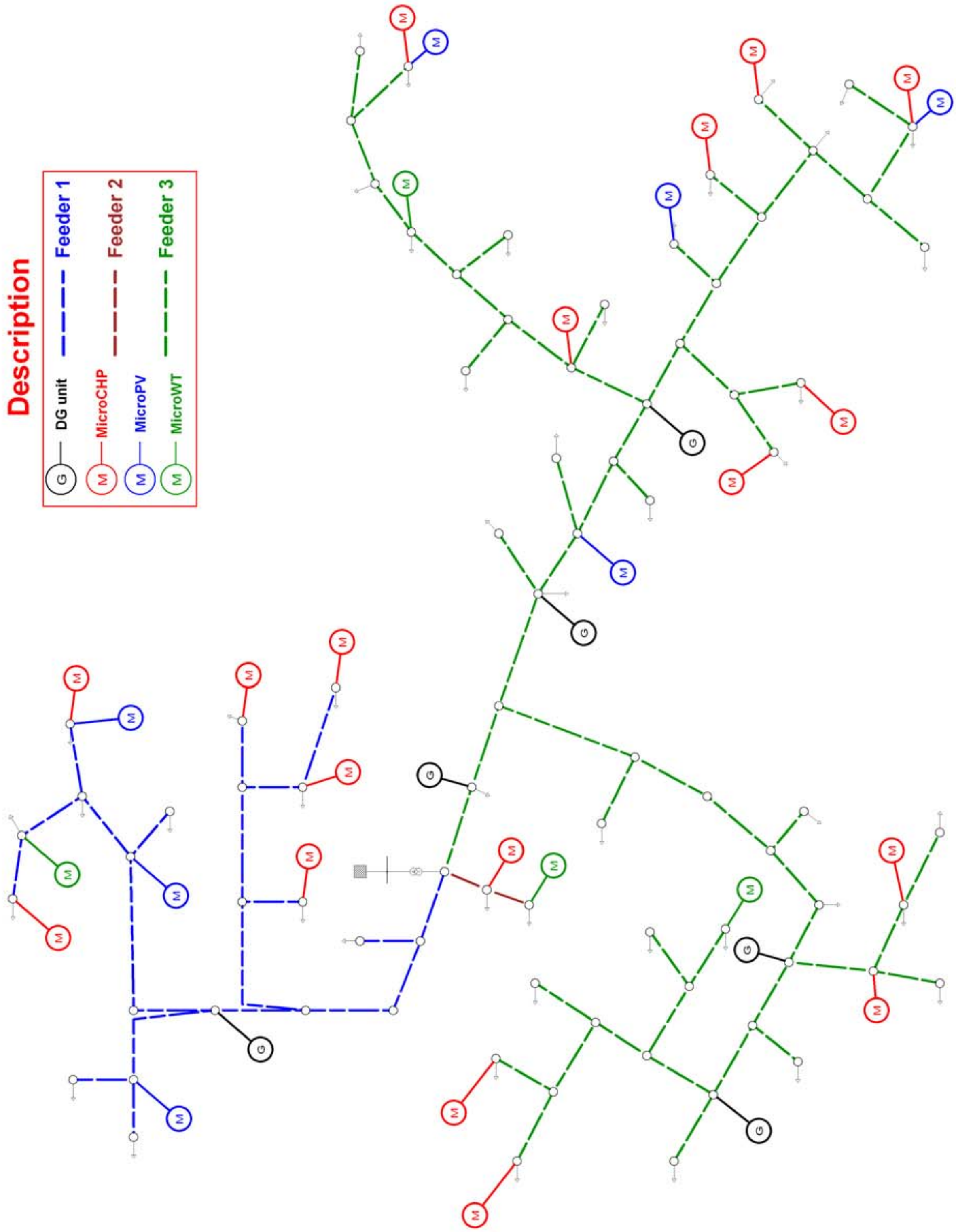

Figure A-47 Urban Microgrid of UK for Scenario 2

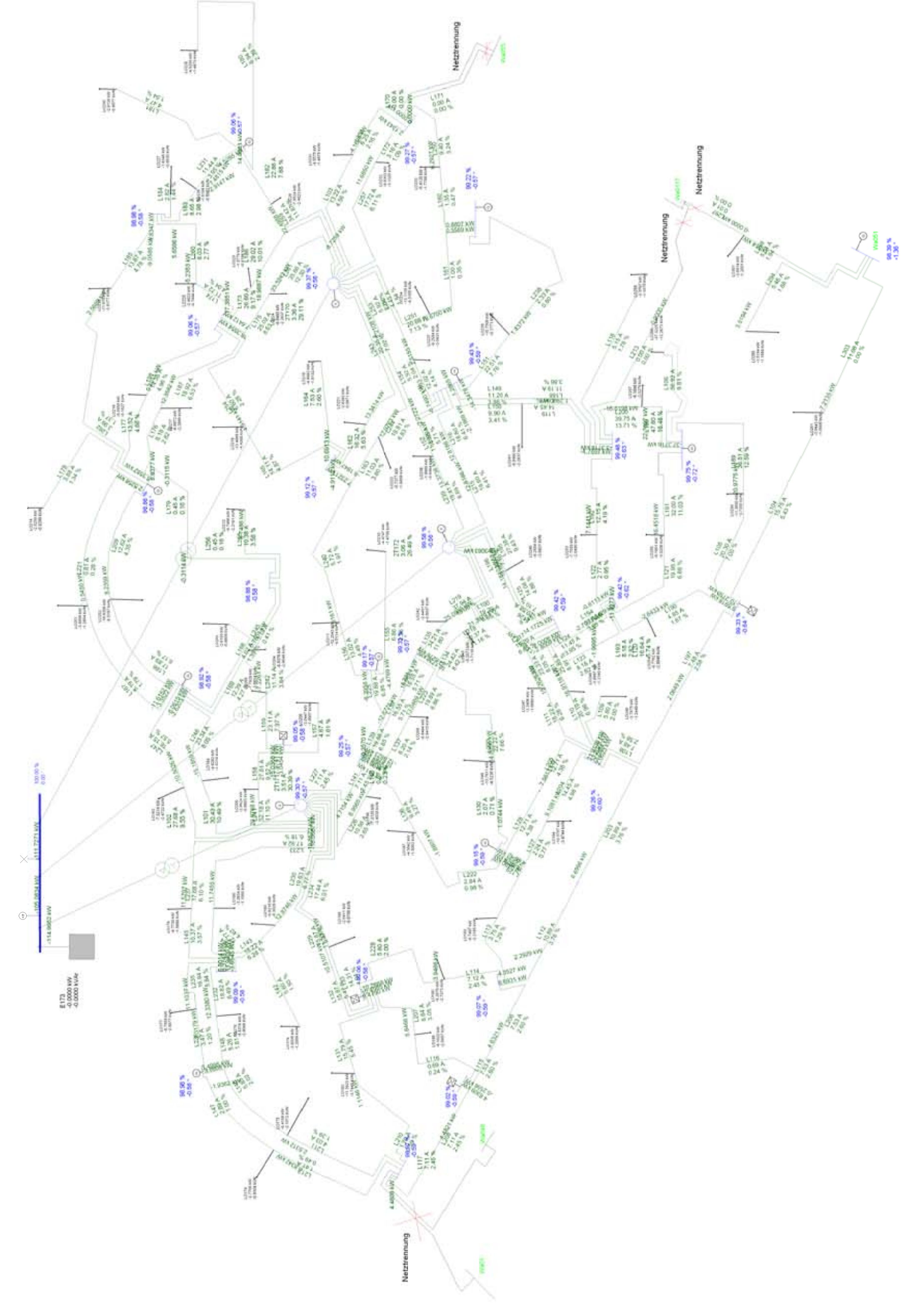

Figure A-48 Microgrid of Germany