Advanced Architectures and Control Concepts for More Microgrids

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Content

Technical Annex

List of Abbreviations

CAES	Compressed Air Energy Storage
CAMC	Central Autonomous Microgrid Controller
CHP	Combined Heat and Power
d-	Link Variable Difference (Outgoing Minus Incoming)
DG	Distributed Generation
DMS	Distribution Management System
DSB	Demand Side Bidding
DSI	Demand Side Integration
DSM	Demand Side Management
DSO	Distribution System Operator
ED	Economic Dispatch
FC	Fuel Cell
FIT	Feed In Tariff
FLH	Full Load Hour
GA	Genetic Algorithm
GALV	Genetic Algorithm Low Voltage
-i	Incoming Link Variable
IPP	Independent Power Producer
J	Jacobian Matrix
L	Loop Index Matrix
LC	Load Controllers
LP	Linear Programming
LV	Low Voltage
M	Evolution Matrix
MC	Local Microsource Controllers
MCDA	Multi Criteria Decision Aid
MG	Micro-Generator
MGCC	Microgrid Central Controller
MMG	Multi-Microgrid
MS	Micro-Source
MT	Micro-Turbine
MV	Medium Voltage
NPV	Net Present Value
NtL Method	Node-to-Link Load Flow Method
-o	Outgoing Link Variable
OPF	Optimum Power Flow
P	Active Power

PV[1]	Constant Active Power and Voltage Magnitude Type
PV[2]	Photovoltaic
Q	Reactive Power
QP	Quadratic Programming
RES	Renewable Energy Resources
RTU	Remote Terminal Units
SHP	Small Hydro Plant
STC	Standard Test Condition
T	Link-to-Node Correlation / Deduction Matrix
TD	Decoupled Link-to-Node Correlation / Deduction Matrix
ToU	Time of Use
U	Voltage Magnitude
UC	Unit Commitment
UoS	Use of System
VD	Node-to-Difference Voltage Deduction Matrix
VPP	Virtual Power Plant
WT	Wind Turbine
α	Voltage Angle

Microgrid Benefit Indices

Commercial Benefit:	LCB as Local Consumer Benefit
	MSB as Dispatchable Micro-Source Benefit
	NHV as Network Hedging Value
Technical Benefit:	RPL as Reduction of Peak Loading
	RVV as Reduction of Voltage Variation
	RSL as Reduction of System Loss
	RII as Reliability Improvement Index
Environmental Benefit:	TER as Total Emission Reduction

Description of Networks

UMV	Urban medium voltage (network)	ULV	Urban low voltage (network)
RMV	Rural medium voltage (network)	RLV	Rural low voltage (network)

Country Abbreviations

DE	Germany	NL	The Netherlands
DK	Denmark	PL	Poland
GR	Greece	PT	Portugal
IT	Italy	UK	United Kingdom
MA	Macedonia		

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Executive Summary

A Microgrid is essentially an aggregation concept with participation of both supply- and demand-side resources in low-voltage (LV) distribution grids. Based on the synergy of local load and local Micro Source (MS) generation, a Microgrid could provide a large variety of economic, technical, environmental, and social benefits to both internal and external stakeholders. In comparison with peer MS aggregation methods, a Microgrid offers maximum flexibility in terms of ownership constitution, allows for global optimization of power system efficiency, and appears as the best solution for motivating end consumers via a common interest platform. In addition, Microgrids could accelerate the commercialization of comparatively expensive renewable energy resources (RES) as well as enhance network hosting capacity for intermittent RES units.

The economic values created by a Microgrid can be roughly categorized into locality benefit and selectivity benefit. Locality benefit is mainly attributed to the creation of an internal 'over-the-grid' energy market within Microgrid, where MS units could sell at prices higher than wholesale level and end consumers could buy at prices lower than retail level. Selectivity benefit, on the other hand, is primarily associated with optimization of real-time dispatch decisions that maximize opportune profit or minimize opportune loss of the complete Microgrid with consideration of technical and environmental constraints.

In order to fully achieve the potential economic benefits of a Microgrid, proper market and regulatory settings need to be applied beforehand. Firstly, recognition of local (i.e.,' over-the-grid') energy trading is the minimum requirement for making a Microgrid financially feasible to build. Secondly, application of real-time instead of constant pricing scheme introduces more trading opportunities for MS units—especially in countries and regions with low electricity prices. Finally, introduction of favourable trading prices and RES support measures (e.g. feed-in tariff) could further enhance Microgrid profitability and create a more level-playing field for different MS technologies.

A Microgrid could potentially improve the technical performance of local distribution grid mainly in the following aspects: (1) energy loss reduction due to decreased line power flows; (2) mitigation of voltage variation via coordinated reactive power control and constrained active power dispatch; (3) relief of peak loading of constrained network devices through selective scheduling of nearby MS outputs; and (4) enhancement of supply reliability via partial or complete islanding during loss of main grid. When the total number of Microgrids reaches a sufficiently high share in LV substations, similar technical benefits can be expected in upstream grids as a consequence of multi-Microgrid operation.

The actual level of technical benefits explored from a Microgrid, however, depends strongly on two factors: the optimality of MS allocation and the degree of coordination among different players. Just as effective planning of MS dimensioning and interconnection decisions could maximize unit contribution to system performance, unguided penetration of oversized MS units at weak grid points could create more technical problems than benefits in the end. Nonetheless, potentially asynchronous development of market price and load demand within a well-designed Microgrid could still lead to situations where technical benefits need to be achieved at the cost of MS profitability—therefore, a real time, multi-unit coordination platform in either centralized or decentralized form is needed to maintain targeted Microgrid technical performance at all times.

Environmental benefits of a Microgrid can be expected from two sources: shift toward renewable or low-emission (e.g. natural gas) fuels and adoption of more energy efficient energy supply solutions (e.g. combined heat and power applications). Due to the application of EU emission trading scheme and widespread national support policies for renewable resources, the fuel-

switching credit of Microgrid is expected to grow as RES cost goes down (leading to wider adoption) over the years. Application of CHP and district heating and/or cooling concepts, on the other hand, varies significantly from region to region and is expected to find considerably different levels of acceptance across Europe.

Finally, social benefits of Microgrids can be mainly expected from three aspects: (1) raising public awareness and fostering incentive for energy saving and GHG emission reduction; (2) creation of new research and job opportunities; and (3) electrification of remote or underdeveloped areas. All of these listed impacts, however, can be seen as long-term effects and are more quantitative rather than qualitative in nature.

In scope of this report, Microgrid benefits are identified on a grid-to-grid basis using a variety of input data from different countries and regions. In order to pinpoint the actual Microgrid benefits arsing from different real-time operation conditions, each case study has been simulated as a consecutive day-to-day Microgrid scheduling problem with annual stochastic weather, market, and demand data. A multi-objective optimization algorithm has been adopted for transferring technical and environmental impacts to either economic objectives or operation constraints, for which a novel optimal power flow technique is used in combination with meta-heuristic methods to estimate real-time system states. Reliability improvements and social benefits, however, can be seen as independent from daily Microgrid operation and are thus studied separately.

Study results indicate that large confidence intervals are expected for literally all economic, technical, and environmental benefit indices deducted from Microgrids in different countries and regions. However, despite individual differences a general convergence of Microgrid behaviour under varying sensitivity entries can be observed. Statistical analysis of obtained results also suggests that estimated energy self sufficiency level (demand side) of a Microgrid can be used as a good indication for potential value estimation of the majority of benefit indices. Sensitivity studies, in the mean time, confirmed the previously claimed necessity for proper market, regulatory, and design settings.

Recommendations are given in the end for different stakeholders that might be potentially involved with Microgrids.

1 Introduction

1.1 The Microgrid Concept as a Means to Integrate Distributed Generation

During the last decades, the deployment of distributed generation (DG) resources has been growing steadily. In this process, the power distribution utilities have been one of the industry's most concerned stakeholders. The main reason is that DGs are connected primarily within their distribution networks, mainly at Medium Voltage (MV) and High Voltage (HV) level, which have been designed under the paradigm that consumer loads are passive and power flows only from the substations to the consumers and not in the opposite direction. For this reason, many studies on the interconnection of DG within distribution networks have been carried out, ranging from control and protection to voltage stability and power quality among many others ([1], [2]).

However, different micro-generation technologies, such as micro-turbines (MT), photovoltaic (PV), fuel cells (FC) and wind turbines (WT) with a rated power ranging up to a hundred kWs can be directly connected to the Low Voltage (LV) networks. In this context, micro-generation units, typically located at users' sites, have emerged as a promising option to meet growing customer needs for electric power with an emphasis on reliability and power quality and contribution to different economic, environmental and technical benefits.

Furthermore, it has to be recognized that with increased levels of micro-generation penetration, the LV distribution network can no longer be considered as a passive appendage to the transmission network. On the contrary, the impact of micro-generation at LV levels on power balance and grid frequency may become much more significant.

Therefore, a control and management architecture is required in order to facilitate full integration of micro-generation and active load management into the system. One promising way to realize the emerging potential of micro-generation is to take a system approach which views generation and associated loads as a subsystem or a Microgrid [3].

Moreover, the control and management of such a system should account for all the benefits expected to be seen at all voltage levels of the distribution network. Therefore, different hierarchical control strategies need to be adopted at different network levels.

The possibility of managing several Microgrids, DG units directly connected to the MV network and MV controllable loads introduces the concept of a Multi-Microgrid. The hierarchical control structure of such a system requires an existence of intermediate control level, which will optimize the Multi-Microgrid system operation, assumed to be operated in real market environment.

The impact that such a system may have on the distribution network may lead to different regulatory approaches by creating incentive mechanisms for the Distribution System Operators (DSO), micro-generation owners and loads to accept the Multi-Microgrid concept and define adequate remuneration schemes. Multi Criteria Decision Aid (MCDA) techniques as well as optimisation algorithms based on genetic algorithms allowing a combined optimisation of energetic, economic and environmental aspects will be used as a potential way to capture different Decision Maker's preference structures when analysing the potential benefits and costs coming out of the Microgrid and Multi-Microgrid concepts deployment.

1.2 Clarification of the Microgrids Concept

1.2.1 What is a Microgrid?

In the preceding research project '*Microgrids: Large Scale Integration of Micro-Generation to Low Voltage Grids*', a definition of Microgrid has been given in deliverable DC1 [7] :

Microgrids comprise LV distribution systems with distributed energy resources (microturbines, fuel cells, PV, etc.) together with storage devices (flywheels, energy capacitors and batteries). Such systems can be operated in a non-autonomous way, if interconnected to the grid, or in an autonomous way, if disconnected from the main grid. The operation of micro-sources in the network can provide distinct benefits to the overall system performance, if managed and coordinated efficiently.

There are three major messages delivered from this definition, namely as:

1. Microgrid is an integration platform for supply-side (micro-generators) and demand-side resources (storage units and (controllable) loads) located in a local distribution grid.
   - In the Microgrid concept, there is a focus on local supply of electricity to nearby loads, thus aggregator models that disregard physical locations of generators and loads (such as virtual power plants with cross-regional setups) are not Microgrids.
   - A Microgrid should contain supply-side resources, and likely demand-side resources are also included in the same time. It is typically located in LV level with total installed micro-generator capacity below MW range, but there can be exceptions [8].

2. A Microgrid should be capable of handling both normal state (grid-connected) and emergency state (islanded) operations.
   - The majority of future Microgrids will be operated for most of the time under grid-connected condition except for those built on physical islands, thus main benefits of Microgrid concept will arise from grid-connected (i.e. 'normal') operating states.
   - Long-term islanded operation of an entire Microgrid poses high requirements on storage size and capacity ratings of micro-generators. However, reliability benefits of under-designed Microgrids (i.e. cannot enter island mode without load shedding measures) can still be quantified from partial islanding of important loads.

3. The difference between a Microgrid and a passive grid penetrated by micro-sources lies mainly in the way of management and coordination of available resources.
   - A Microgrid operator is more than an aggregator of small generators, or a network service provider, or a load controller, or an emission regulator—it performs all these functionalities and serves multiple economic, technical, and environmental aims.
   - One major advantage of the Microgrid concept over other 'intelligent' solutions lies in its capability of handling conflicting interests of different stakeholders so as to arrive at a globally optimal operation decision for all players involved.

A Microgrid could appear in a large variety of scales—examples for Microgrids as a LV grid, LV feeder, or LV house are given in Figure 1-1, Figure 1-2, and Figure 1-3 respectively. As a Microgrid grows in scale, it will be likely equipped with more balancing capacities and feature better controllability due to reduction of intermittency from both load side and Renewable Energy Resources (RES) side. However, in general the maximum capacity of a Microgrid (in terms of peak load demand) is limited to several MW (European scale), above which Multi-Microgrid concepts will apply by dividing the aggregated units into interconnected but separate Microgrids.

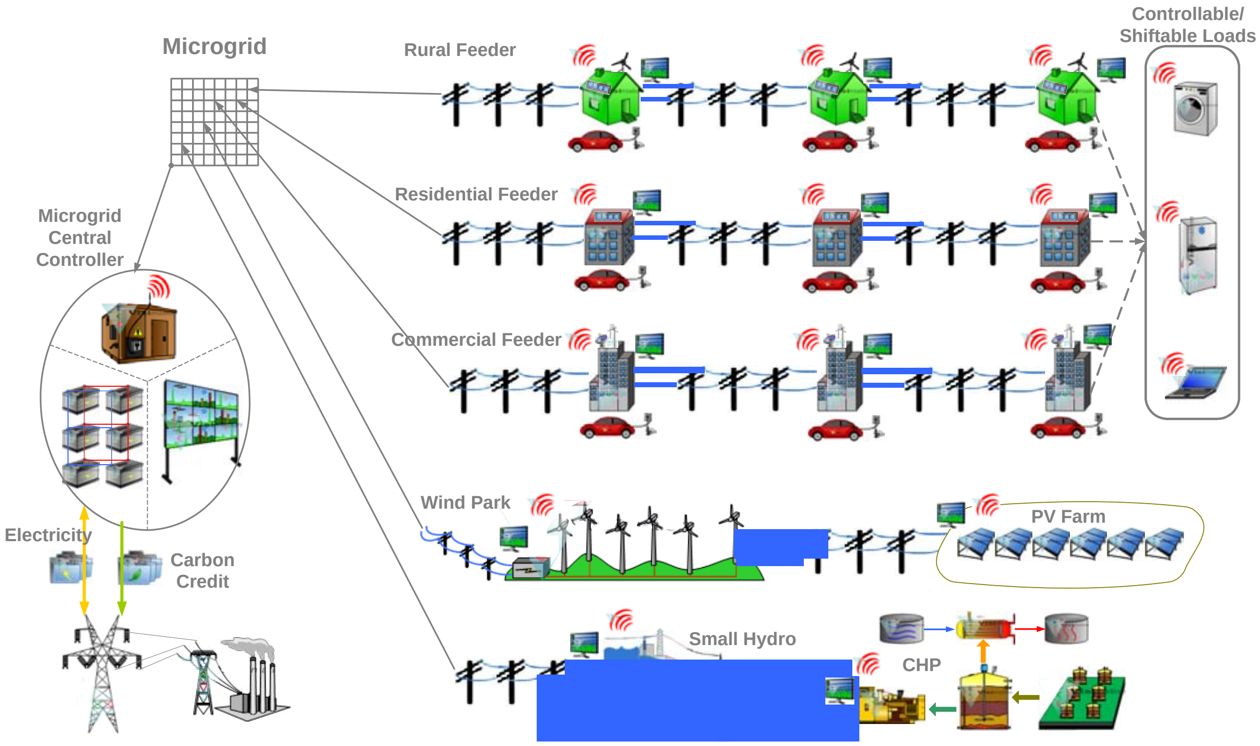


Figure 1-1 Sample Microgrid as a LV grid

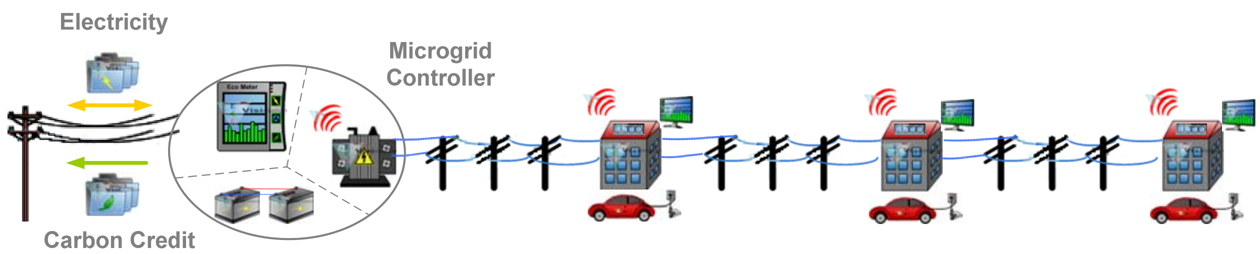


Figure 1-2 Sample Microgrid as a LV feeder

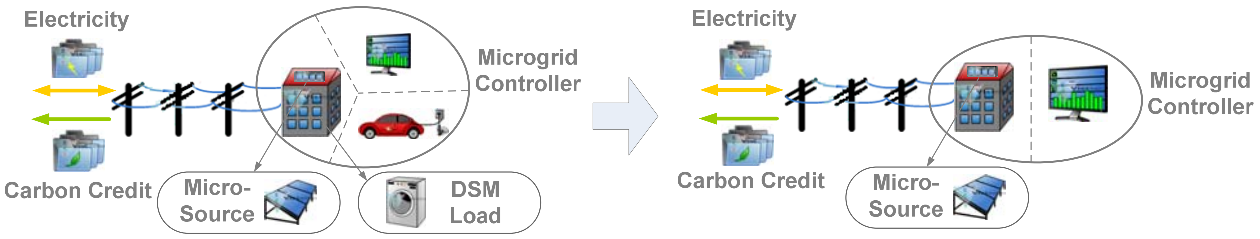


Figure 1-3 Sample Microgrid as LV House

1.2.2 What is not a Microgrid?

Figure 1-4 aims to further clarify the Microgrid concept by providing examples for essential Microgrid components.

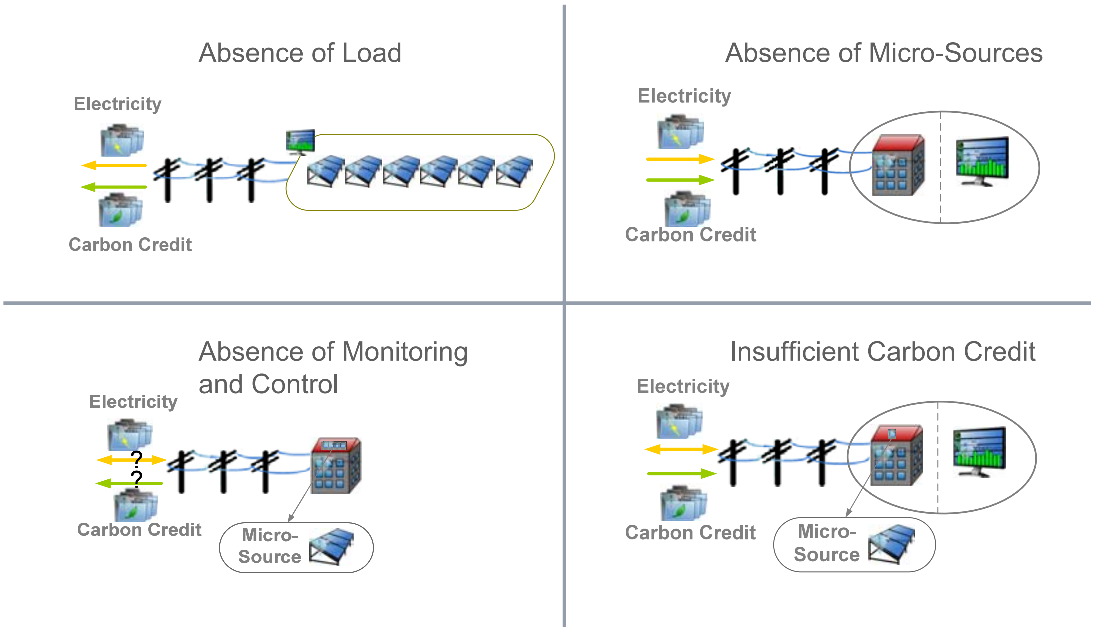


Figure 1-4 What Isn't a Microgrid: Sample Cases

Current misconceptions are clarified in the following section:

- I have customers that equip themselves with PV and micro wind turbines, and I also own several small hydro and CHP plants, so I must have a Microgrid.

⇒ DG penetration is indeed a distinct Microgrid feature, but Microgrid means more than passive tolerance of DG and needs active supervision, control, and optimization.

- Microgrids are full of intermittent renewable energy resources, so they must be really unreliable and easily subject to failures and total black-outs.

⇒ A Microgrid can offset RES fluctuation by its own storage units (when islanded) or external generation reserves (when grid-connected). And Microgrids' capability of converting from grid-connected to island mode actually improves security of supply.

- Microgrids must be so expensive to build that the concept will be limited to field tests.

⇒ Widespread financial support schemes for RES and CHP have already ensured the basic profitability of a nowadays Microgrid, in future reductions of micro-generation and storage costs can make Microgrids commercially competitive.

- The Microgrid concept is just another energy retailer's advertising trick to increase his income.

⇒ Even if an end consumer chooses not to buy the photovoltaic panels on his roof top or hold a share in the community-owned CHP plant, he can still benefit from having more choices of energy supply and sharing carbon-reduction credits in his bill.

- The Microgrid controllers will force me to use my computer in office when there is enough sunshine and to switch on washing machine at home when the wind is blowing.

⇒ Demand Side Integration (DSI) programs in normal commercial and household applications should apply 'load follow generation' control philosophy only to long-term stand-by appliances (such as refrigerators and air-conditioners) or time-insensitive devices (such as water heater).

- A Microgrid is such a totally new idea, that system operators need to rebuild their entire network.

⇒ Although extensive metering, communication, and control devices needed to be installed in extra, conversion of a normal 'passive' distribution grid to Microgrid does not actually incur too much infrastructure costs on network operator side—in contrary, a Microgrid can actually defer investment costs for device replacement.

- Since I am the participant of a Microgrid, I will never have any supply interruptions.

⇒ 'Smooth' (i.e. no loss of load) transition to island operation is only possible with large storage or generation redundancy within a Microgrid, thus an islanded Microgrid will shed unessential loads according to instantaneous amount of available resource.

1.2.3 Terminology of Microgrid Components

In scope of this report, a number of different terminologies have been used for generator and storage units within or outside of a Microgrid, which are listed and clarified as follows:

- *DG (Distributed Generation):* generators both within and outside of a Microgrid
- *RES (Renewable Energy Sources):* DG units that are renewable (mostly intermittent)
- *CHP (Combined Heat and Power):* generation technology that by default refers to heat-driven types, and that can be electricity driven in case with sufficient thermal storage (as explained in section 4.1.2)
- *DER (Distributed Energy Resources):* generator, (controllable) load and storage units on LV and MV levels
- *MS (Micro-sources):* generators within a Microgrid; it has to be distinguished between dispatchable MS such as electricity driven CHP units and non-controllable units, i.e. intermittent renewable generation
- *Dispatchable MS: Micro Sources that are primarily gas-fired and fully dispatchable, used as major source of control power within a Microgrid*

1.3 Barriers, Enablers, and Expected Benefits of Microgrids

Taking the Microgrid definition into account it is expected to achieve technical network improvement, to gain economic benefits and to reduce environmental aspects.

Barriers, enablers, and critical signals for Microgrid development are respectively listed below:

Barriers to a Microgrid Future

- *Deep connection charge applied to MS units*
- *Forbiddance of local ('over-the-grid') energy trading*
- *Extremely low electricity prices and time-invariant tariff*
- *Negligence of locational, environmental, and efficiency value of small MS units*
- *Lack of information transparency concerning real time network conditions*

Enablers for Microgrid Acceptance

- *Development of local retail and local service markets within Microgrids*
- *Application of real-time price setting to Microgrids*
- *Continuous electricity price increment due to increasing fossil fuel scarcity*
- *Size-specific, location-specific, technology-specific MS incentive programs*
- *Widespread social concern and commitment over global warming effect*

Critical Signals for Microgrid Implementation

- *RES (esp. PV) cost reduction*
- *Storage (esp. battery) cost reduction*
- *Widespread enforcement of smart grid concept*
- *Widespread adoption of smart metering devices*
- *Widespread adoption of plug-in electric vehicles (E-cars)*

1.4 Microgrids versus VPP Concept

Three main differences between Microgrid and VPP concept can be identified:

1. Size (small vs. anything from small to large)
2. Locality (local concern vs. traditional power trading strategy)
3. Demand Interest (end consumer interest expressed somehow vs. only DSI remuneration)

One important Microgrid advantage over VPP is the reduction of intermediary parties (lower transaction cost), as shown in Figure 1-5. This is simply due to the merging of retailer and VPP functions in a single Microgrid setup.

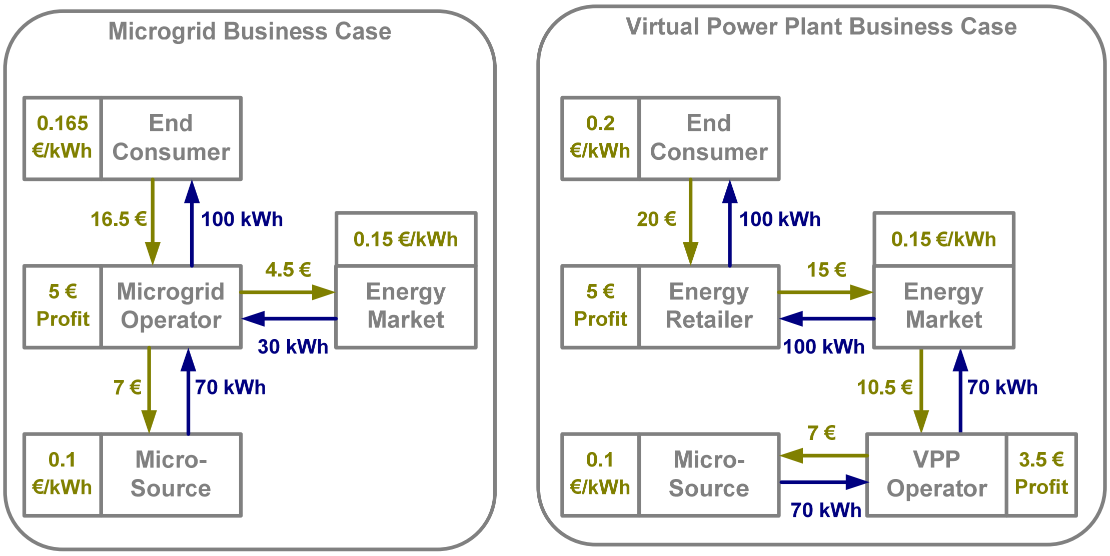


Figure 1-5 Microgrid Benefit Over VPP due to Intermediary Reduction

In addition, a VPP tends to deny local consumption (except for load management for negative balancing power) as it is a virtual generator, while Microgrids acknowledges local power consumption and gives end consumer the choice of purchasing local generation with privileged tariff. The integration of both demand and supply sides also leads to better controllability for Microgrids, as shown by Figure 1-6, where simultaneous optimization of both supply and demand resources becomes possible with Microgrid application.

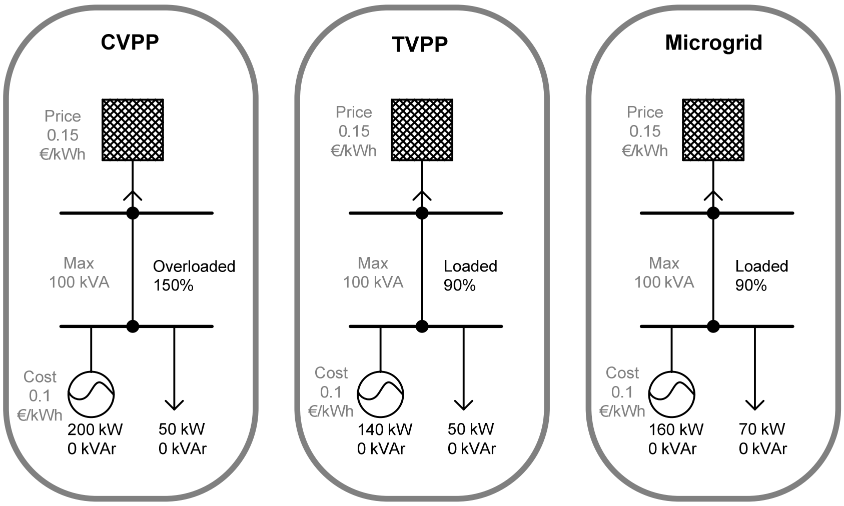


Figure 1-6 Microgrid Benefit Over VPP due to Supply Side Integration

1.5 Microgrid Control

Technically, Microgrids are emerging as an outgrowth of micro-generation in the LV networks, via the application of emerging technologies, especially power electronic interfaces and modern controls. Therefore, a controlled grouping of energy sources and sinks connected to a LV grid, but as well having the possibility of functioning independently (islanded manner), can serve as a possible definition of a Microgrid. The possibility of actively managing the network through the Microgrid concept is central to the evaluation of Microgrid and integration of this capability is a key requirement whenever Microgrid operation appears as an option. The coordinated operation and control of micro-sources together with storage devices such as flywheels, energy capacitors, batteries, and controllable loads such as water heaters and air conditioners is central to the concept of a Microgrid ([4], [5]). From the grid's point of view, a Microgrid can be regarded as a controlled entity within the power system that can be operated as a single aggregated load, and given attractive remuneration, even as a small source of power or ancillary service supporting the network. From a customer's point of view, Microgrids similar to traditional LV distribution networks not only provide their thermal and electricity needs, but in addition, enhance local reliability, reduce emissions, improve power quality by supporting voltage and reducing voltage dips, and lead to lower costs of energy supply. It is clear that, in order to achieve these benefits, it is important to provide a management and control structure, so as to balance demand and supply coming both from the micro-sources and the Medium-Voltage (MV) distribution feeder.

Hierarchical control scheme architecture comprising three different control levels, has been assumed for a Microgrid operation, as shown in Figure 1-7:

- Local Microsource Controllers (MC) and Load Controllers (LC);
- Microgrid Central Controller (MGCC);
- Central Autonomous Management Controller (CAMC).

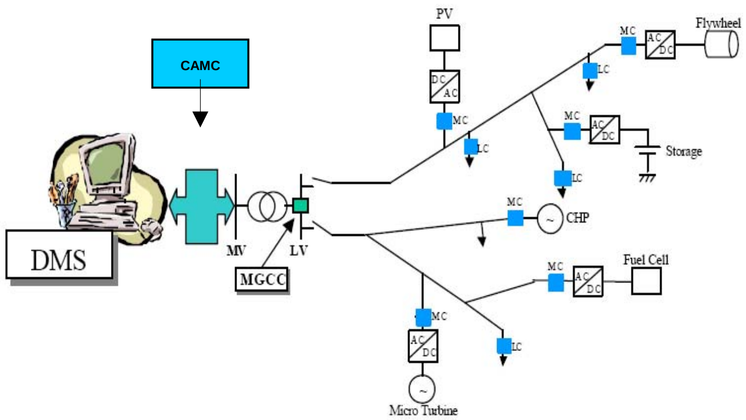


Figure 1-7 Microgrid Control and Management Architecture

The local MC takes advantage of the power electronic interface of the micro-generation units within the Microgrid. It uses local information to control the voltage and the frequency of the Microgrid in transient conditions. MCs follow the demands from the MGCC, when connected to the power grid, and perform local optimization of the micro-generation active and reactive power production, and fast load tracking following an islanding situation. Local LC controllers installed at the controllable loads provide load control capabilities following orders from the MGCC for load management.

The MGCC is responsible for the maximization of the Microgrid value and the optimization of its operation. It uses the market prices of electricity and gas to determine the amount of power that the Microgrid should draw from the distribution system, thus optimizing the local production capabilities. The defined optimized operating scenario is achieved by sending control signals to the MCs and LCs. In this framework, noncritical, controllable loads can be shed when necessary, subject to Demand Side Bidding (DSB). Thus, consumers within the Microgrid might bid for their loads supply for the next hour in the same m-min intervals. The information exchange within a typical Microgrid is as follows: every m min, e.g., 15 min, each micro-source bids for the production for the next hour in m-min intervals. These bids are prepared according to the energy prices in the open market, the operating costs of the micro-generation units plus the profit of the micro-generation owner, and other needs for the installation facility, e.g., space heating. For example, if a micro-generation owner has installed a CHP unit, it may wish to provide heat demand locally at a certain period. For this period, the bids sent to the MGCC should aim at maximizing this profit by participating in the electricity market. In market terms, the MGCC might represent the functions of an aggregator or energy service provider, who acts in the interest of one or more Microgrids [4].

The MGCC optimizes the Microgrid operation according to the open market prices, the bids received by the micro-sources, and the forecasted loads, and sends signals to the MCs of the micro sources to be committed, and if applicable, to determine the level of their production. In addition, consumers within the Microgrid might bid for their loads supply for the next hour in the same m-min intervals or might bid to curtail their loads. In this case, the MGCC optimizes the operation based on micro-sources and load bids, and sends dispatch signals to both the MCs and LCs [5].

The optimization procedure depends on the market policy adopted in the Microgrid operation [5].

1.6 Microgrid Management Strategies

It is assumed that each consumer has low- and high-priority loads allowing him to send separate bids to the MGCC for each of their types by placing his bids in two levels reflecting his priorities. “Low” priority loads can be satisfied in periods of lower prices (shift) or not be served at all (curtailment). A similar approach can be used for more than two bid levels reflecting more precisely the consumer’s priorities. Two options are considered for the consumers’ bids [5].

Shift option: Consumers place two different bids for the supply of their high- and low-priority loads in the next operating periods;

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

In both options, the MGCC:

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

The MGCC optimizes the Microgrid operation according to the bids of both micro-generation and loads. In the shift option, the MGCC sums up the micro-sources bids in ascending order and the demand-side bids in descending order in order to decide which micro-sources will operate for the next hour and which loads will be served. Optimal operation is achieved at the intersection point of the producers’ and consumers’ bids [5].

In the curtailment option, consumers bid for part of their load they are willing to shed in the next time intervals, if compensated.

Two types of micro-generation units are considered under this approach:

- Controllable (fuel consuming units);
- Non-controllable (RES units).

In addition, it is assumed that the consumers within the Microgrid are price sensitive, therefore, subjected to demand side bidding, offering lower price for satisfying part of their load considered as noncritical load and therefore accepting the possibility of shifting that load for the next hour when the electricity market price is considered “acceptable” for satisfying the non-critical load. Taking this into account, very probable, we might face sudden reconnection of the entire noncritical load at a certain hour, thereby causing technical constraint violation. Therefore, “smoother” reconnection is assumed to take place, by even distribution of the noncritical load between two consequent hours of “acceptable” electricity prices. Additional constraint is that the entire noncritical demand needs to be satisfied by the end of the day, i.e. by the hour of 24.

As described in [5] at each time interval, MGCC is provided with:

- Electricity market prices in €/kWh, assumingly, the same applied to the consumers within the Microgrid;
- The active and reactive power demand, probably as a result of a short term load forecasting tool.
- The bids of the micro-generation units within the Microgrid.

This information prices influences consumer bids, i.e. might shift load for a while in order to achieve lower costs for their electricity consumption. The total Microgrid demand at each hour is modified by the summation of the shifted load at each LV node from/to that hour. Since the demand bids are of discrete nature, there is no optimization process to determine the “exact” operating points for the controllable loads.

Fuel consuming units within the Microgrid, such as MT and FC units are considered as controllable ones, whose production level is subjected to a local optimization problem, performed by the MGCC. Therefore, MGCC optimizes the Microgrid operation according to the open market prices, the bids received by the micro-generation controllable units within the Microgrid, and the forecasted loads, and sends signals to the MCs of the micro-generation controllable units to be committed, and if applicable, to determine the level of their production.

The production of the RES based micro-generation units, like wind turbines (WT) and photovoltaic (PV) arrays cannot be regulated and their output is determined by the availability of the primary source, i.e., wind or sun radiation. Therefore, they are referred as non-controllable units.

The unit commitment (UC) problem is first solved using a priority list. The micro-generation bids, the load bids, if DSB options are implemented, and the market prices are placed in one list according to their differential cost at the highest level of production for the specific period. This list is sorted in ascending order, until the total demand is met.

The MGCC tries to minimise the energy costs for the whole Microgrid solving the following optimization problem for each time interval, i.e. hour under a certain market policy [5].

$$mincost = \sum_{i=1}^{N} a_i \cdot x_i + b_i + AX \tag{1-1}$$

Subject to:

Active power balance equality constraint:

$$X + \sum_{i=1}^{N} x_i = P_{demand} \qquad (1\text{-}2)$$

Technical limits of each unit:

$$P_i^{min} \leq x_i \leq P_i^{max} \qquad (1\text{-}3)$$

The first term in (1) refers to the bid of each controllable micro-generation unit within the Microgrid, where bi represents the hourly payback amount for the investment and a_i is their variable cost, i.e., fuel cost. The RES are usually remunerated through feed-in tariffs being always dispatched providing that the primary source is available. In all cases, the terms b_i and c_i should also consider the expenses for the communication and control infrastructure that is essential for the coordinated control of the micro-generation units in Microgrid operation. At the present pace of technological development, however, this cost is expected to be only marginal compared to the installation and fuels cost and will not be considered in the analysis. The term bi should also include start-up costs, only when the unit is not in operation or is still in a start-up state. x_i is the active power production of the i-th micro-generation unit within the Microgrid, X is the active power bought from the grid, N is the number of the micro-generation units that offer bids for power production, and A is the open market active power price. At this control level a shift option has been assumed for the DSB, not being subject to the local optimization procedure due to the discrete nature of the load bids. The cost related to the compensation for the controllable load assuming curtailment option has not been included in (1-1) due to the assumption that no load has been curtailed under the local optimization procedure (1-1). Curtailment of the controllable load has been assumed within special curtailment contracts activated under global optimization procedure, performed at CAMC level, described furthermore in the report.

Economic dispatch (ED) is performed next so that the production settings of the controllable micro-sources within the Microgrid, i.e., diesel units, micro-turbines, etc., and the power exchange with the grid are determined.

1.7 Multi Microgrid Control and Management Structure

The extension of the concept introduces a higher level structure, named Multi-Microgrid (MMG), formed at a MV level, consisting of several LV Microgrids connected to adjacent MV feeders. However, in this research it is assumed that no other DG sources are installed in the MV network, since the objective of this study regards the evaluation of the MMG impact at MV level.

The technical operation of such a system requires transposing the Microgrid concept to the MV level where all the Microgrids, as well as MV/LV passive substations, will be controlled by a higher control level, namely, CAMC to be installed at the HV/MV substation, serving as an interface to the Distribution Management System (DMS) under the responsibility of the DSO. In fact, the CAMC may be seen as one new DMS application that is in charge of one part of the MV network.

One of the key issues when dealing with Multi-Microgrid operation is an adequate control and management strategy operated in decentralized manner due to the tremendous increase in dimension and complexity of the system. Nevertheless, decision making using decentralized control strategies must still hold a hierarchical structure. A central controller should collect data from multiple agents and establish rules for the lower ranked individual agents.

These rules for each controller must be set by high level central management system (DMS) which may delegate some tasks in other lower level controllers (CAMC or MGCC). In this case, a purely central management would not be effective enough because of the large amount of data to be processed and treated, and therefore would not ensure an autonomous management namely during islanded mode of operation. The CAMC must then communicate with other "local" controllers such as MGCC or with micro-sources or loads connected to the MV network, serving as an interface for the DMS.

Therefore, the CAMC will be playing a key role in a Multi-Microgrid system: it will be responsible for the local data acquisition process, for enabling the dialogue with the DMS upstream, for running specific network functionalities and for scheduling the different agents in the downstream network, receiving information from the upstream DMS, measurements from the Remote Terminal Units (RTU) located at the MV network and existing MGCC. It will also have to deal with constraints and contracts to manage the Multi-Microgrid in both HV grid-connected operating mode and emergency operating mode as well as in stressed operating conditions when some of the technical constrains, in terms of congestion levels and voltage drops, are likely to be violated.

The suggested hierarchical control system can be represented by the block diagram in Figure 1-8 where it is shown how to possibly implement the level 2 and level 3 controls autonomously, without any intervention from the DMS [6]. The CAMC will be the entity from where the commands for production change will be originated. The CAMC does not need to know the specific Microgrid constitution as each of the Microgrids is controlled and somewhat "hidden" by the corresponding MGCC. However, the CAMC will still be able to perform control actions directly over other micro-generation units, usually of bigger size than the ones under MGCC control. Figure 1-9 illustrates a Multi-Microgrid control structure with communication relations among the control levels.

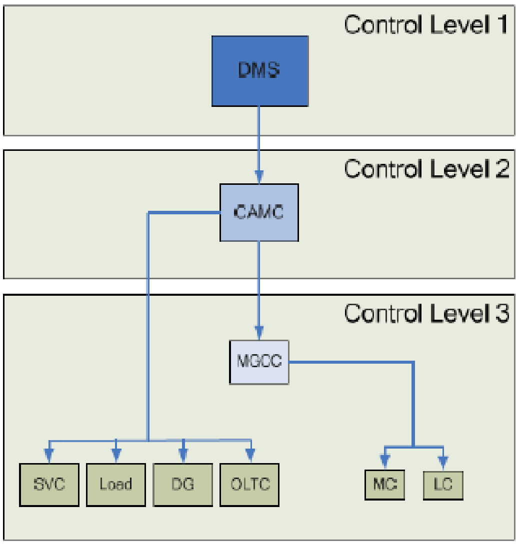


Figure 1-8 Hierarchical control scheme

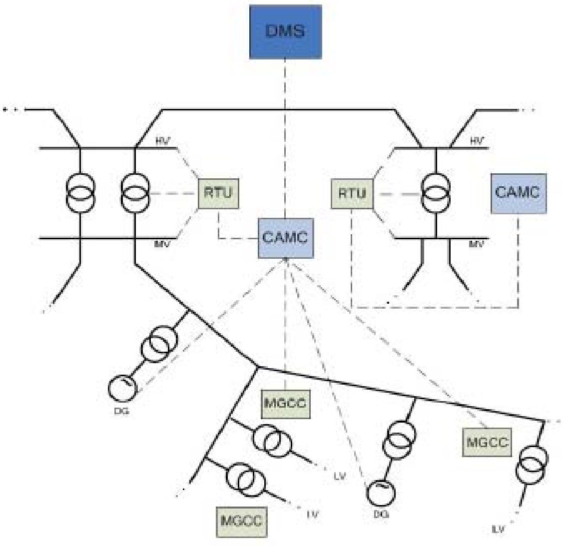


Figure 1-9 Multi Microgrid control structure

2 Microgrid Benefits Identification

2.1 Economic and Financial Aspects of Microgrid Deployment

2.1.1 Microgrid as an Initiator of Local Retail and Service Markets

For most Microgrids, the main players in the market are micro-sources (MS) in the form of DG such as PV and micro-CHP units, whose profitability will largely determine the commercial feasibility of Microgrid implementation. It has been acknowledged in multiple studies [9] [10] that potential benefits of DG are mostly local in nature and are thus generally faced with recognition problems under current regulation and trading schemes. Thus the Microgrid concept can be seen as a key driver for realizing profitable operation of DG due to its capability of providing local identification and pricing of DG-created values. Specifically, two potential sectors can be explored from Microgrid concept: retail and service markets.

2.1.1.1 Local Retail Market

When financial support schemes are absent, the majority of modern DG technologies are not yet economically competitive in wholesale electricity markets except for providing peak-shaving support when hourly prices are high [12]—which inevitably leads to quite low full load hours (FLH) for DG and slow return of investment. There are arguments, however, in favour of granting retail tariff instead of wholesale price to DG [13] so as to stimulate local supply of energy, which in reality faces large implementation obstacles as such measures could potentially undercut profits of local utilities or energy suppliers [14]. The Microgrid concept, however, provides a middle way between under-pricing and over-pricing of distributed energy resources (DER), which offers a local retail market where internal consumption of electricity from micro-sources can be traded under dynamic supply-demand equilibriums.

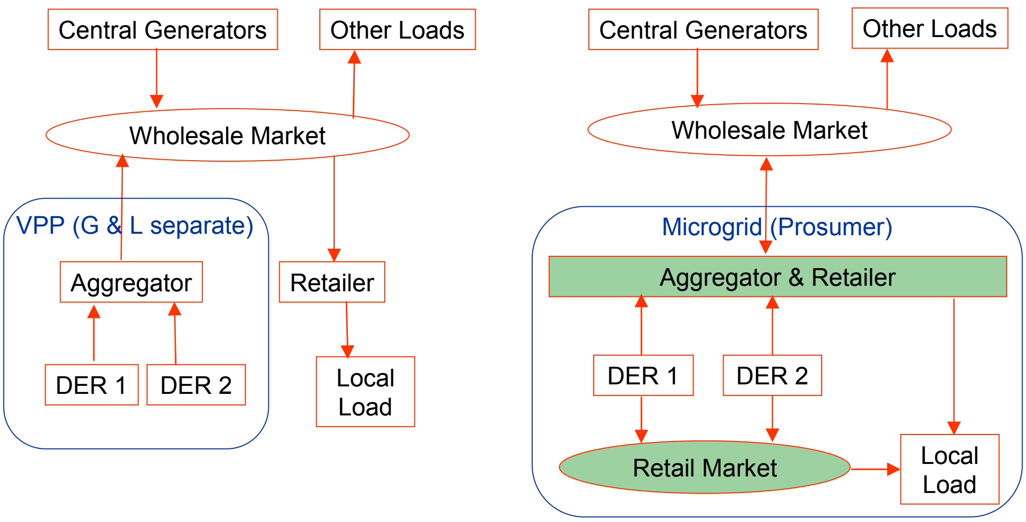


Figure 2-1 Illustration of Differences between VPP and Microgrid Concepts

The capability of hosting a local retail market directly between micro-sources and end consumers tells Microgrid concept apart from other aggregator models such as VPP (virtual power plant) etc., as shown in Figure 2-1. Technical aspects of the distribution can be considered in parallel with commercial aggregation aspects. However, the concept of location-specific market goes against the common conception of electric industry that energy produced from any generator in the grid should be freely available to any customer at any location of the grid [17]. Therefore the acceptance of Microgrid concept will be a challenge. Thus quite imaginably, the same statutory obstacles that impede DER adoption will also impede Microgrid deployment, while legislations that do not discriminate against DG or even favour DG might actually discourage Microgrid deployment in the end (such as regulations that provide special tariffs for aggregated DG units but only allow them to sell their outputs to the wholesale market).

Arguments could arise concerning the necessity of listing local market as a mandatory feature of Microgrids, as technically a grid-connected Microgrid may still be operated without a problem when financial interactions between local load and local generation are strictly banned. However, a Microgrid should be able to provide an integration platform for both supply-side and demand-side players, which implies that any specific value created within a Microgrid is the outcome from the synergy of local load, local generation (if applicable local storage) and local network. Thus complete decoupling of DG interests from the concerns of end consumers in a Microgrid could easily lead to overlook of such potential values and eventually undermine overall system performance. Therefore the bottom line of a Microgrid here is that distinctions should at least be made concerning the part of load supplied from DG and the part of load supplied from external import, and the value of self-sufficiency should be identified with a price signal.

Obviously, it is not an easy task to carve out a new retail market for DER from the solid standing of existing market structures in whatever European country under study. Regulators need to introduce at least two changes of current legislation:

(1) To allow aggregation of both generation and load and acknowledge local trading

(2) To allow autonomous management of a network section as a Microgrid

It should be noted that potential promoters of a local retail market are not limited to DER owners or operators: in [11] a local energy community initiative has been proposed by a consortium of residential end consumers. Both environmental awareness and concerns over increasing electricity price could lead to strong demand-side motivations for a Microgrid solution. In this sense, the Microgrid concept can be seen as an aggregated extension of on-site generation or self-generation, but with a broader level of concern in terms of geographical and energetical scopes.

2.1.1.2 Local Service Market

In preceding discussions of local retail market (chapter 2.1.1.1), interactions between local load and local generation within a Microgrid have been explored; there is however a second possibility of local market formulation between local generation and local network, which resembles the existing network service market between TSO and central generators but is both much smaller in scale and more location-restricted. Such a service market is essential for recognition of technical contribution of micro-sources to the LV grid where Microgrid is located.

In Figure 2-2, a background is laid out to illustrate the potential formulation of technical service markets for DER located at different voltage levels. As micro-sources are generally located within the network sections where their technical services should apply, it can be difficult to identify the recipient(s) of such services—while some arguments propose that DER service should be traced up to the highest voltage level and deserve both DSO and TSO recognition [18], the most convenient and natural identification approach will limit DER contribution to the voltage level of its interconnection and address local DSO only [20]. The introduction of Microgrid and Multi-Microgrid’ (i.e. MV-scale Microgrid) concepts, however, makes it possible to allow an aggregated group of small DER units to take part in the service market of a higher voltage level, as shown by dotted lines in Figure 2-2.

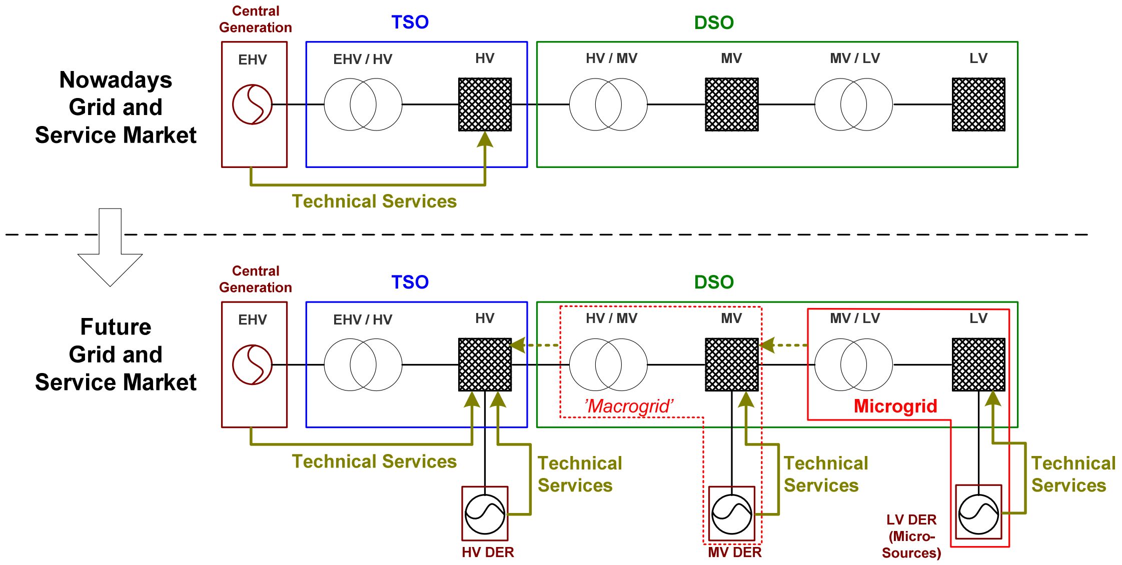


Figure 2-2 Provision of Network Service in Nowadays and Future Grids

In general, five main types of technical services can be potentially traded between DSO and micro-sources in a Microgrid:

1. Frequency support (load following) service via control of active power
2. Voltage support service via control of reactive power
3. Peak loading and power loss compensation service
4. Islanding and black-start support service
5. Balancing power supply service

It should be noted that not all DER units are capable of providing all service types listed above—for example, PV and WT are not capable of controlling their active power output (in best case only a down-regulation is possible due to limited availability of RES), thus will not be eligible for providing any frequency, islanding, or balancing support services. In addition, since distribution grids are generally weaker than transmission networks and DER sizes are normally quite small in comparison with local network capacity, achievement of a technical aim might require coordinated efforts of multiple DER units, which could lead to complicated reward allocation schemes.

2.1.2 Microgrid as an Aggregator of Both Supply- and Demand-Side Players

A Microgrid should be able to provide an open trading and communication platform for supply-side players such as micro-sources and central generators as well as demand-side players such as storage devices, loads controlled via DSM (demand side management) measure, and normal end consumers. Under grid-connected condition, transactions within a Microgrid will be performed on both internal (local retail) and external (general wholesale) markets, which imbues Microgrid operator with two basic functionalities: local balancer and back-feeder, which can be seen from Figure 2-3. Obviously, clearance of each balancing state should be accompanied with simultaneous closure of transactions in both local retail market and external wholesale market, thus Microgrid operator is also responsible for synchronizing times schedule of local market with that of wholesale market.

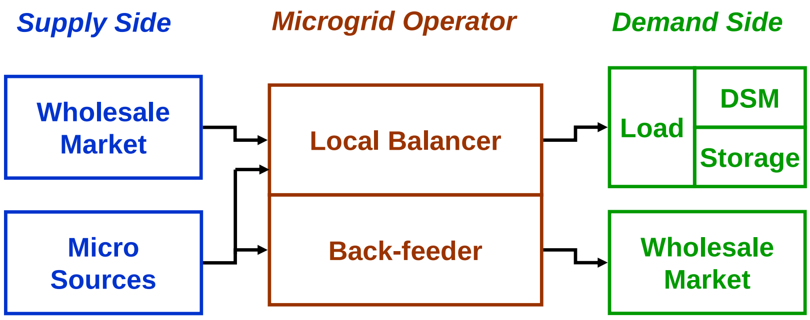


Figure 2-3 Supply- and Demand-Side Players in a Microgrid

Both Figure 2-1 and Figure 2-3 indicate that a distinct feature of Microgrid concept, when compared to the aggregator models proposed in EU-DEEP [12] and FENIX [13] projects, is that a Microgrid could represent the interests of not only micro-sources but also common end consumers within it. This extra flexibility allows for easier DER adoption from the customers' point of view—this is especially true when a set of PV panels need to be installed on a customer's rooftop or when a potential CHP unit is about to take up a large share of a customer's cellar space, quite obviously only passive or even depreciative reactions can be expected if the customer neither owns the unit(s) for self-generation nor enjoys any reduction in electricity tariff by buying directly from these resources (in case he does not own or operate them). A Microgrid solution makes it possible to disseminate the values created from micro-sources not only to end consumers that participate in a DSI program, but also to normal 'passive' customers that simply submit a 'Yes' vote for Microgrid and agree to tolerate any potential inconveniences from it.

For different stakeholders, aggregation values of a Microgrid are respectively as follows:

1. To DER units: acquisition of real-time wholesale price and favourable selling tariff;
2. To end consumers: chance to buy potentially cheaper electricity from local DER;
3. To DSO: easier contracting and trading procedures (reduction of individual entries);
4. To energy supplier and local retailer: unification of both entities.

2.1.3 Microgrid as a Hedging Tool against Potential Risks

In general, the initial investment decision of Microgrid might be made by different stakeholders under different motivations, but very likely the economic drive behind will be a concern over potential risks in future. In Figure 2-4 a short summary of such risks and correlated stakeholders is given, which can be seen as the applicable justifications for investing in Microgrid to use it as a hedging tool.

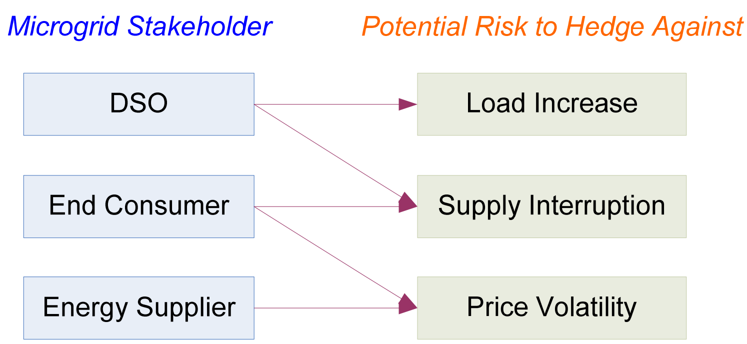


Figure 2-4 Microgrid Stakeholders and Potential Risks of Their Concerns

In the finance sector, hedging refers to risk management strategies used in limiting or offsetting probability of loss from fluctuations in the prices of commodities, currencies, or securities [21]. When examined under the context of power industry, a hedging manoeuvre can be mainly interpreted as an investment decision in hardware and/or software of a power grid aimed at reducing or avoiding potential future costs or revenue losses due to external uncertainties or risks. As can be seen from Figure 2-4, hedging target of a Microgrid can be increasing loading levels in the network (which could cause premature replacement of infrastructure [23]), or an unreliable transmission network that has high outage rate (such as the case of US [24]), or a volatile electricity market price that shows rising average and extremely high peak values [26].

Figure 2-4 also exhibits that different stakeholders may have different or similar interests in terms of using Microgrid as a hedging tool—a DSO might invest in a Microgrid to shave potential load peaks to defer replacement of certain infrastructures or to improve its supply reliability; and a consortium of end consumers might raise money to purchase their own DER units for self-generation so as to fight against rising retail tariff and high black-out frequencies; while an energy supplier might choose to expand its energy portfolio with a number of DER units to offset high price peaks from wholesale market. Noticeably there are overlapped concerns from DSO and end consumer over supply interruption; and similarly from end consumer and energy supplier over price volatility.

As can be expected from every investment, the major initial investor(s) of a Microgrid will also expect to be the major benefactor(s) in the end. Thus operation strategy and interest allocation scheme of a Microgrid could vary to a large extent according to if it is owned by DSO, or energy supplier, or end consumer, or multiple or all stakeholders.

2.1.4 Microgrid as an Interest Arbitrator for Stakeholders

In comparison with passive aggregation models, the Microgrid concept allows arbitration of cost and revenue entries associated with transactions in both internal and external markets. This functionality is especially important under deregulated market conditions when complications from both energy and cash flows could lead to difficulties in direct 'over-the-counter' solutions between supply- and demand-side stakeholders. In order to illustrate this problem, a sample Microgrid energy flow state is shown in Figure 2-5.

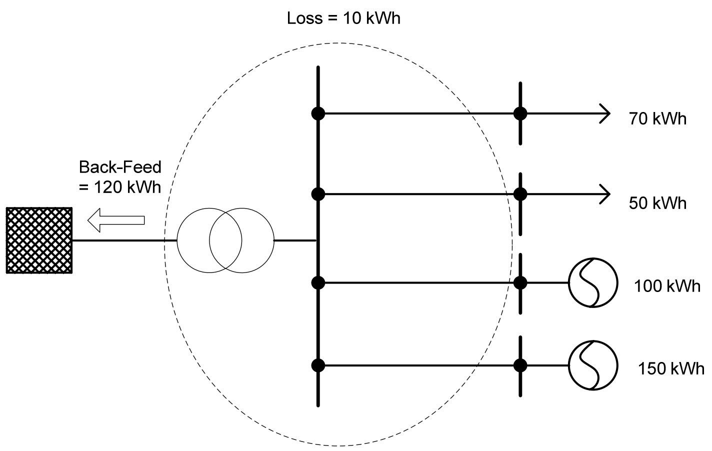


Figure 2-5 Sample Hourly Energy Flow in a Microgrid

Obviously, when the major stakeholders (load, DER, wholesale market) in Figure 2-5 are left on their own to decide the sender, receiver, and amount of payments for this balance state, confusions are likely to occur between the generators as to 'who is selling how much to local load and to the external market', or between the loads as to 'who is buying how much from local generation and from the external market'. It is therefore the task of Microgrid operator to settle this issue by collecting and sending clear price signals from and to the stakeholders in real time, as shown by the deregulated example in Figure 2-6.

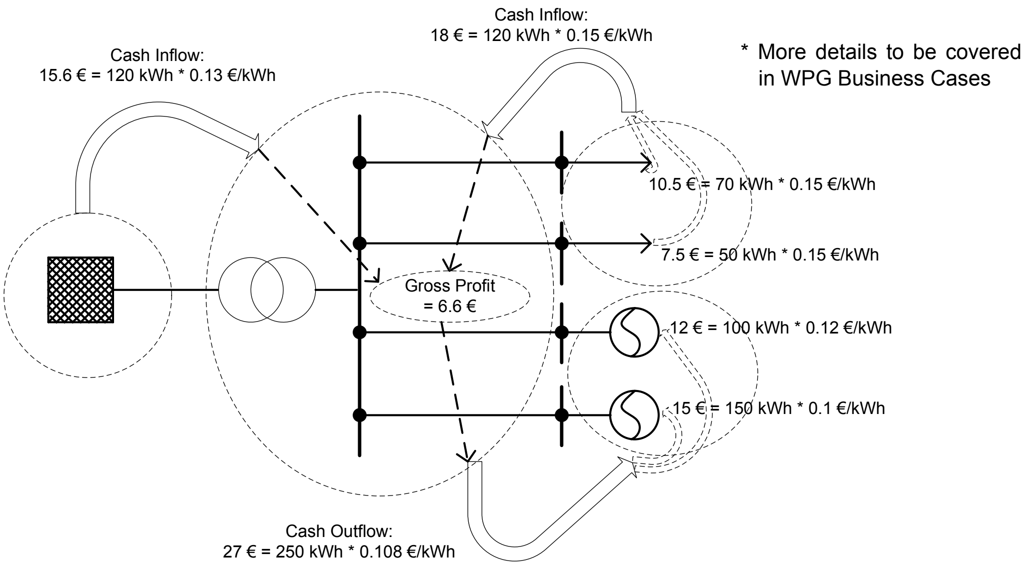


Figure 2-6 Sample Cash Flow in a Microgrid under Arbitration

2.2 Technical Aspects of Microgrid Deployment

Aside from economic considerations, strong technical incentives from DSO perspective can sometimes also play crucial roles in Microgrid adoption. This is especially true for the cases when DER investment is made by individual or load-side entities, which leaves DSO a comparatively lighter economic burden of providing metering, control, and communication devices and services for the Microgrid.

In comparison with economic benefits, potential technical values that can be created from a Microgrid are more difficult to identify and remunerate—the local service market proposed in section 2.1.1.2 can be seen as one viable option, but obviously there is no guarantee for it to cover all technical aspects. Nonetheless, the transparency ('hidden' or 'visible' to service market) of technical values created by a Microgrid will only affect interest allocation schemes (i.e. business cases under deregulated condition), while it has basically no impact on the identification and classification of such benefits.

Although it is also possible to obtain the majority of Microgrid technical benefits listed in ensuing sections with passive DER units, the coordination platform offered by Microgrid concept makes it possible to expand such benefits to more sections of the grid, more critical moments around the year, and more simultaneous achievements of multiple purposes. Thus rather than attributing the accomplish of one or more technical aim(s) to a specific DER unit under control, a Microgrid tends to view any technical outcome as the simultaneous work of all controlled grid components. This would of course need complicated reward schemes, as already shown in section 2.1.1.2.

Finally, all technical discussions in this section will be focused on stead-state aspects of Microgrid operation, as for a DSO most economic values will derive from them.

2.2.1 Peak Shaving Potentials of a Microgrid

A Microgrid can contribute to the deferral of potential infrastructure investments via reduction of peak loading in critical sections of the power system. In Figure 2-7, two typical cases of peak line loading reduction are exhibited with a simplified Microgrid structure.

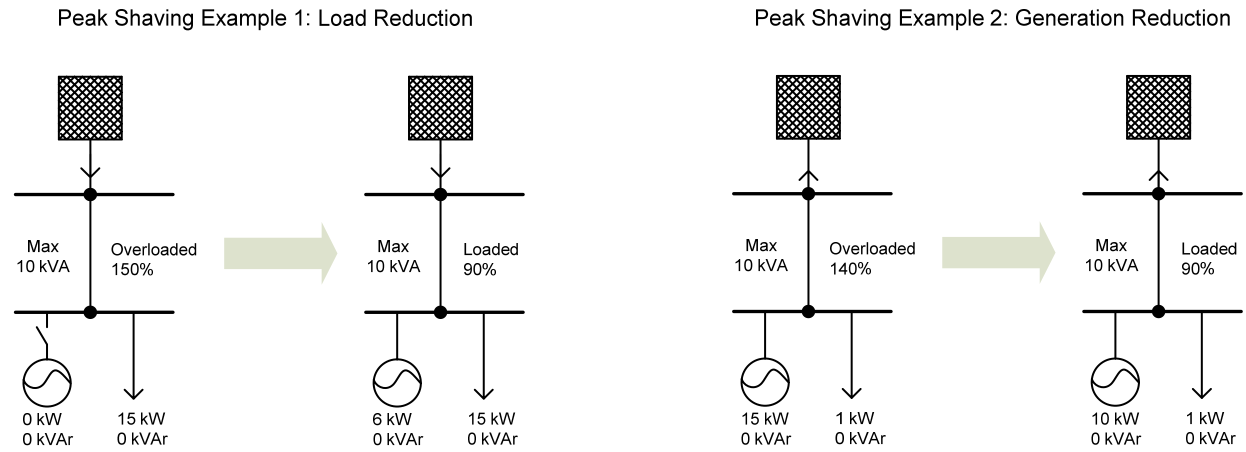


Figure 2-7 Examples of Peak Shaving in a Simplified Microgrid

For the first case of peak shaving in Figure 2-7, the Microgrid attempts to mitigate peak load consumption by switching on stand-by generation capacity or maximizing the output of available micro-generators that are located on the load-side of a heavily-constrained line. Although this idea appears to be simple, in reality financial or regulatory obstacles might make it difficult to implement. For example, if the local peak loading coincides with a very low wholesale price, then with a generator-only aggregation model (e.g. VPP) the DER unit might decide not to sell any power to the wholesale market at all, while a totally profit-driven Microgrid operator might also choose to buy from the wholesale market instead of local DER units— which will cause the same overloading in the end.

Consequently, with decoupling of local load peak and wholesale price peak (which is more and more likely to occur with the increase of wind or other renewable resources in Europe [27]), a Microgrid operator may be forced to undertake an opportune profit loss by buying from more expensive local DER so as to prevent overloading of certain network elements. In a deregulated market, this lost value of opportune profit can be seen as transferred to the DSO side in the form of deferred capital investment [30], which can be in turn traded on the local service market between DSO and local energy supplier.

Very similarly, the second peak shaving example in Figure 2-7 has proposed an export reduction scheme via limitation of DER output level. Quite imaginably, when this low-load condition is accompanied either by high market price or by high RES output (if RES units comprise the majority of load-side DER capacity), the Microgrid operator will be forced to forgo a part of its back-feeding sales revenue by curtailing DER output level so as not to overload the preceding line. In comparison with the first case, this generation reduction scenario may experience much more difficulty with recognition in local service market as DSO would tend to consider DER as initiator of overloading problem in the first place and refuse to pay for the forgone revenue. In order to avoid this recognition problem, either over-sized DER penetration should be avoided in the design stage of a Microgrid, or agreement between DSO and DER investor should be made beforehand concerning the necessity and remuneration (if any) of potential peak curtailment when a large DER unit that exceeds local network capacity has to be interconnected anyway.

Up to now, examples shown in Figure 2-7 have only suggested the role of active supply-side players (DER units) in avoiding potential overloading of network components. There are of course similar chances for demand-side players (storage, controllable loads) to reduce (first case) or increase (second case) local consumption to achieve same targets. In the mean time, the examples in Figure 2-7 are also limited to the control of active power for peak shaving purpose, while there are also possibilities of reducing component loading via cheaper reactive power control (albeit generally less effective), which is especially true for load areas with high extraction or injection of reactive power.

Finally, it should be noted that the discussions so far have assumed potential interest conflicts between DSO and DER or between DSO and energy supplier in the attempt to achieve peak shaving effects. Thus the financial compromises (i.e. extra cost or profit loss) made by DER or energy supplier can be viewed as a reminder or signal of the fact that they are actually providing DSO with peak shaving (deferral) service, given sufficient transparency of information in the service market. However, if such compromises do not occur in reality (e.g. peak load always accompanied by peak price), or occur very rarely, or cause only slight differences in balancing sheets of DER operator or energy supplier in the end, the providers of such peak-shaving services will be unaware of their credits since this peak reduction effect is only a by-product of their ‘business as usual’ routines. In this case, DSO will obtain the capital deferral benefit without having to pay for it in the service market, unless regulators specifically demand such payments to be made.

2.2.2 Voltage Regulation Potentials of a Microgrid

Traditionally, voltage control in transmission network is mainly achieved via manipulation of reactive power flow in the grid, which is largely facilitated by small R/X ratios of high-voltage transmission lines. Based on this principle, voltage control force in transmission grids could be obtained via parallel or serial capacitors or inductors, or on-load tap changers of transformers, or automatic voltage regulators of central generator units. In comparison, in low-voltage distribution networks the issue of voltage control has been normally ignored as the grid has been designed and operated as passive in nature.

A Microgrid, however, is expected to deliver equal or even better voltage quality in a LV distribution section when compared to a passive design. Under the stress of increasing load and DER (especially intermittent RES) penetration, voltage regulation measures will be needed for a Microgrid to achieve predefined aims. Aside from cost concern, the biggest obstacle of implementing voltage control in a Microgrid is the effectiveness of reactive power flow manipulation due to large line R/X ratios, as illustrated by Figure 2-8.

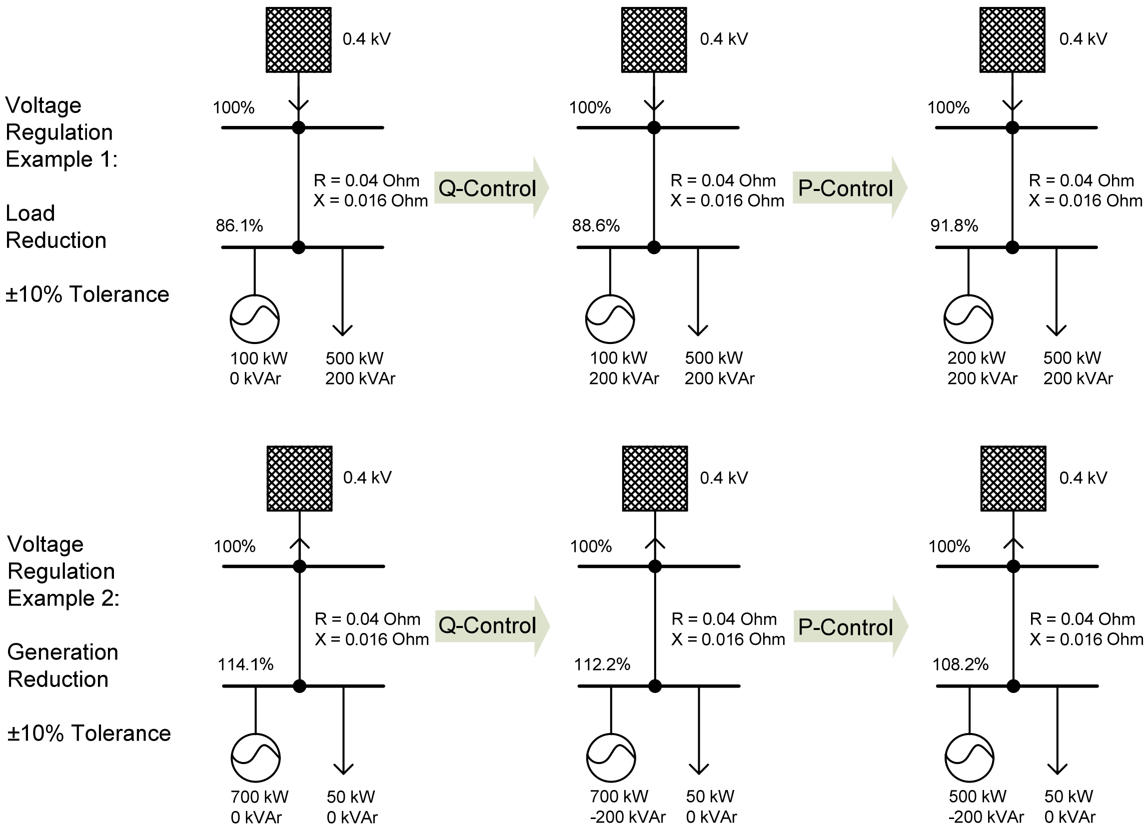


Figure 2-8 Examples of Voltage Regulation in a Simplified Microgrid

For both voltage regulation samples in Figure 2-8, a voltage tolerance band of ±10% has been assumed according to IEC 61050 — of course, each Microgrid can promise higher voltage qualities (e.g. ±5%, ±3% etc.) to its customers as long as the figures are technically feasible to reach. There are potential dangers, however, of not being able to achieve the preset voltage targets solely via reactive power control, which leaves Microgrid operator the only option of manipulating active power flow in the network to keep voltage within range. This is evidenced by the Q-control effects of both sample cases in Figure 2-8: even by depleting the reactive power capacity (200 kVAr) of local DER, the monitored nodal voltage still strays away from preset boundary by -1.4% or +2.2%. An increase or decrease of active power output from local DER will be consequently needed to satisfy the ±10% limit.

Obviously, the potential necessity of resorting to active power management to regulate voltage within a Microgrid poses similar economic complications as those triggered by peak shaving efforts discussed in section 2.2.1. Specifically, when in the same network location overloading and voltage problems arise simultaneously, active power regulation of DER units in vicinity will likely contribute to the solution of both issues and thus deserve double credits in the local service market.

Due to this limited effectiveness of reactive power control over network voltage, a large number of voltage control measures used in transmission level will be difficult or impractical to implement in LV Microgrids—for example, capacitor or inductor banks are not likely to be considered as cost-effective solutions, and automatic voltage regulator concept (Q-U loop control) will show poor applicability to micro-generators (i.e. limited control capability of single units). In addition, there are potential problems with multi-feeder settings [14] [17] when distribution transformers are changed from off-load to on-load tap changer types. Nonetheless, the main voltage control forces in a Microgrid will appear in the form of on-load transformer tap changers and coordinated regulation of reactive and active power outputs of multiple DER units.

Similar to the ‘visibility’ issue of peak shaving credit in local service market, active power regulation decisions that are economically favourable for the Microgrid and in the same time contribute to voltage control are likely to be overlooked as shadow benefits for DSO. However, the same situation is unlikely to happen to reactive power regulation measures of DER, as costs associated with reactive power production from DER are supposed to be remunerated solely in the local service market—open trading of reactive power per volume and flow direction requires a very complicated market mechanism in comparison with service market concept and is thus unlikely to be adopted in reality [31]. Further problems do exist with pricing and identification of contribution from individual DER units in provision of voltage control, which will be detailed in WPH business cases.

2.2.3 Loss Reduction Potentials of a Microgrid

It has been generally acknowledged that DER units—whether controllable or not—could contribute to the reduction of power losses in a network [32]. The Microgrid concept provides a coordination platform that is capable of maximizing loss reduction potentials of both dispatchable and intermittent DER units and performing loss cost allocation under bi-directional power flow conditions [33][36]. As active power outputs of DER units are primarily determined by either external market price (dispatchable DER) or weather condition (intermittent DER), the loss reduction credit of a Microgrid—in comparison with passive grid design—stems mainly from an optimized dispatch of reactive power outputs from DER units with adjustable power factor (via excitation coil or converter interface).

Firstly, in Figure 2-9 a loss reduction scenario is presented with a simplified Microgrid structure. The synergy of local load and local generation conspicuously leads to a lower power loss (0.05 kW) than both load-only (0.43 kW) and generation-only (0.33 kW) scenarios. In this light, the loss reduction credit from a Microgrid, when referenced to an original load-only case with no DER penetration, depends mainly on the ratio of locally-supplied active and reactive power demands within a Microgrid. In the mean time, a more dispersed allocation (i.e. larger numbers and smaller sizes) of DER units could also lead to higher loss reduction credits as more network sections are affected.

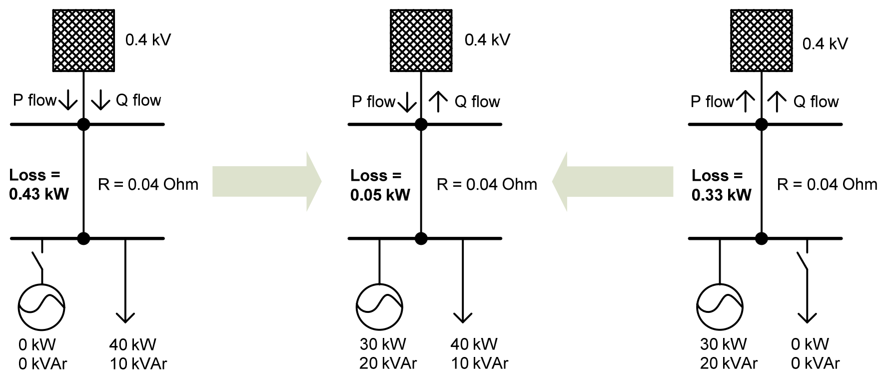


Figure 2-9 Examples of Loss Reduction in a Simplified Microgrid

It should be noted, however, that addition of local DER production does not necessarily always lead to lower power loss compared to load-only condition: i.e., when DER output far exceeds local load. In this case, a Microgrid could mitigate the additional power loss increase via minimization of reactive power flow in the network.

Identification of loss reduction credit from a Microgrid poses a considerable challenge for both system operators and market regulators: for one thing, power loss in a network is constantly changing with power flow conditions and needs to monitored and recorded on-line; for another, the power loss value in each network component is subject to the simultaneous influence of multiple loads and generators, thus allocation of derived loss costs to different players will be a quite complicated task in itself [34]. In order to perform the loss cost derivation task with reasonable complexity and fairness, a simplified algorithm is proposed in WPH business cases, which can be applied to Figure 2-9 as:

When both load and generation units contribute to the power loss of a grid component, active and reactive power flow directions in the component are respectively identified as either load- or generation-orientated: for the sample case, active power flow is load-oriented, while reactive power flow is generation-oriented. Then the active and reactive parts of instantaneous loss cost associated with this component will be credited solely to the units that are responsible for the net power flow—for the sample case, active part of line power loss (0.025 kW) should be paid by local load(s), while reactive part of line power loss (0.025 kW) should be paid by local generator(s). After identification of power flow directions and eligible entity groups (load or generation), loss cost in the component still needs to be attributed to individual units at different locations in the network, which will be also detailed in WPH business case discussions.

2.2.4 Reliability Improvement Potentials of a Microgrid

With sufficient design of generation and storage capacity, a Microgrid can be operated under islanded (off-grid) mode with either the entire network (thus no loss of load) or a fraction of load and generation buses, as illustrated by Figure 2-10. The total islanding case obviously provides an extremely high reliability level for all customers within the Microgrid, while partial islanding could also deliver significant reliability improvement to important loads. For both cases, frequency droop control via rotating inertia or converter characteristics will be needed to allow black-start or switch-off transition from main grid.

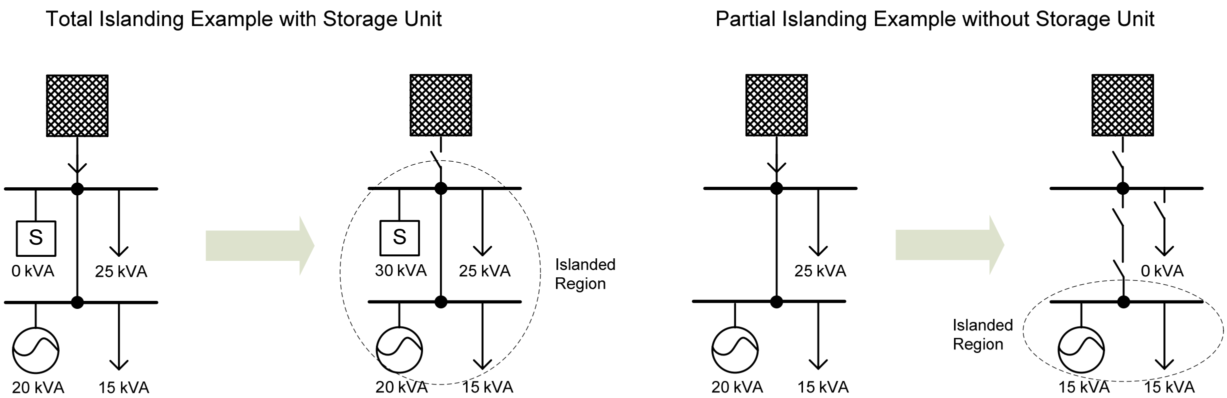


Figure 2-10 Total Islanding and Partial Islanding Samples in a Simplified Microgrid

In contrary to the other technical, environmental and commercial benefits identified in this deliverable that vary due to different operation strategies of different players in the energy market, an improvement in reliability is achieved mainly during the planning phase of Microgrids.

Figure 2-11, suggests a qualitative justification of Microgrid investment in terms of reliability improvement

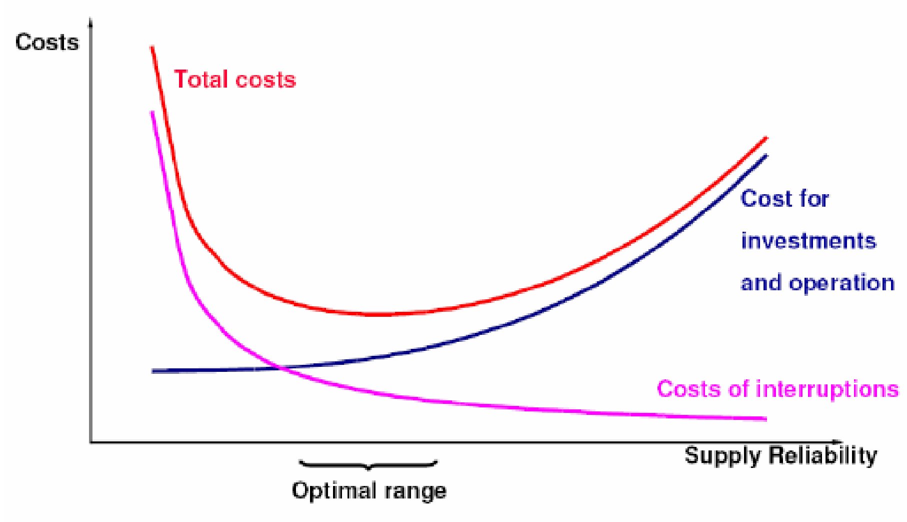


Figure 2-11 Correlation between System Reliability and Financial Cost [18]

A reliability comparison between all European networks identified in deliverable DG1 has been performed and is documented in Annex 4 together with a description of different methodologies to determine reliability contribution of intermittent generation and storage units in Microgrids. Depending on the interruption costs and the given reliability of supply for the network without any micro-sources different benefits are achieved.

Economic Benefits achieved by Reliability Improvement

Figure 2-12 compares the maximum economic benefits of different networks with x-axis as the multiplication of the total load of the network and the unavailability of this network in each year, which is symbolized by PQ. Benefits in each country are almost linear related with PQ as interruption costs without DG increase with increasing total demand and unavailability, leading to higher benefits of Microgrid operation. The higher the outage costs assumed for reliability simulation the higher economic benefits can be achieved as shown for maximum, average, and minimum cost model.

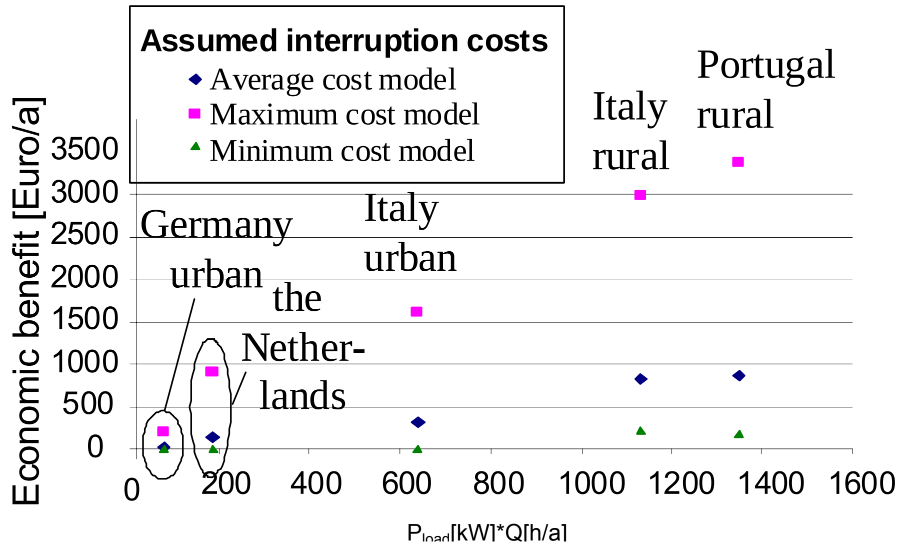


Figure 2-12 Economic Benefit Comparison of Microgrids on European Level

System Reliability Indices

A reduction of system unavailability Q, as one example for system reliability indices, by the installation of micro-sources that enable (partial) island operation is demonstrated in Figure 2-13 for selected European countries, compared to the case without DG.

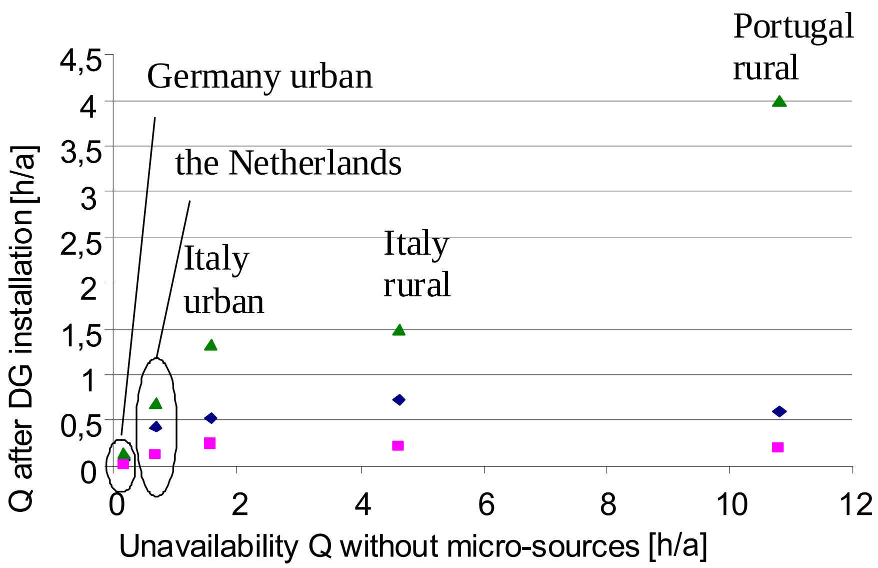


Figure 2-13 System unavailability comparison of different countries

The countries which have worse system reliability achieve higher improvements than the countries with high system reliabilities also in case without DG. For instance, in Portugal rural network the system unavailability decreases from more than 10 h/a to the value of below 1 h/a with maximum and average cost model; even with average cost model yearly unavailability is also reduced to approximate 4h/a. However, the improvement for German urban network and Holland network, which have already good system reliability without micro-sources, is not obvious, although system reliability is also improved to a certain extent in both networks.

With higher interruption cost model, system reliability can be better improved. Higher interruption costs justify higher micro-source investment, thus achieving higher system reliability improvements.

Microgrid operation from reliability point of view is thus most beneficial in countries with lower power quality or in regions or for customer segments with comparably high outage costs.

Optimum DG Penetration Level

One question that most system operators are concerned with is the optimised DG penetration level. Relationship regarding different cost models between optimum DG penetration level and interruption frequency is indicated in Figure 2-14.

Optimum micro-source penetration level is positive related with the interruption frequency without DG penetration; especially for average interruption costs, the relationship is almost linear. This relationship is important for system planning; as the system interruption frequency without DG penetration is generally known, the system operator is able to roughly determine of the optimum DG penetration level from reliability point of view.

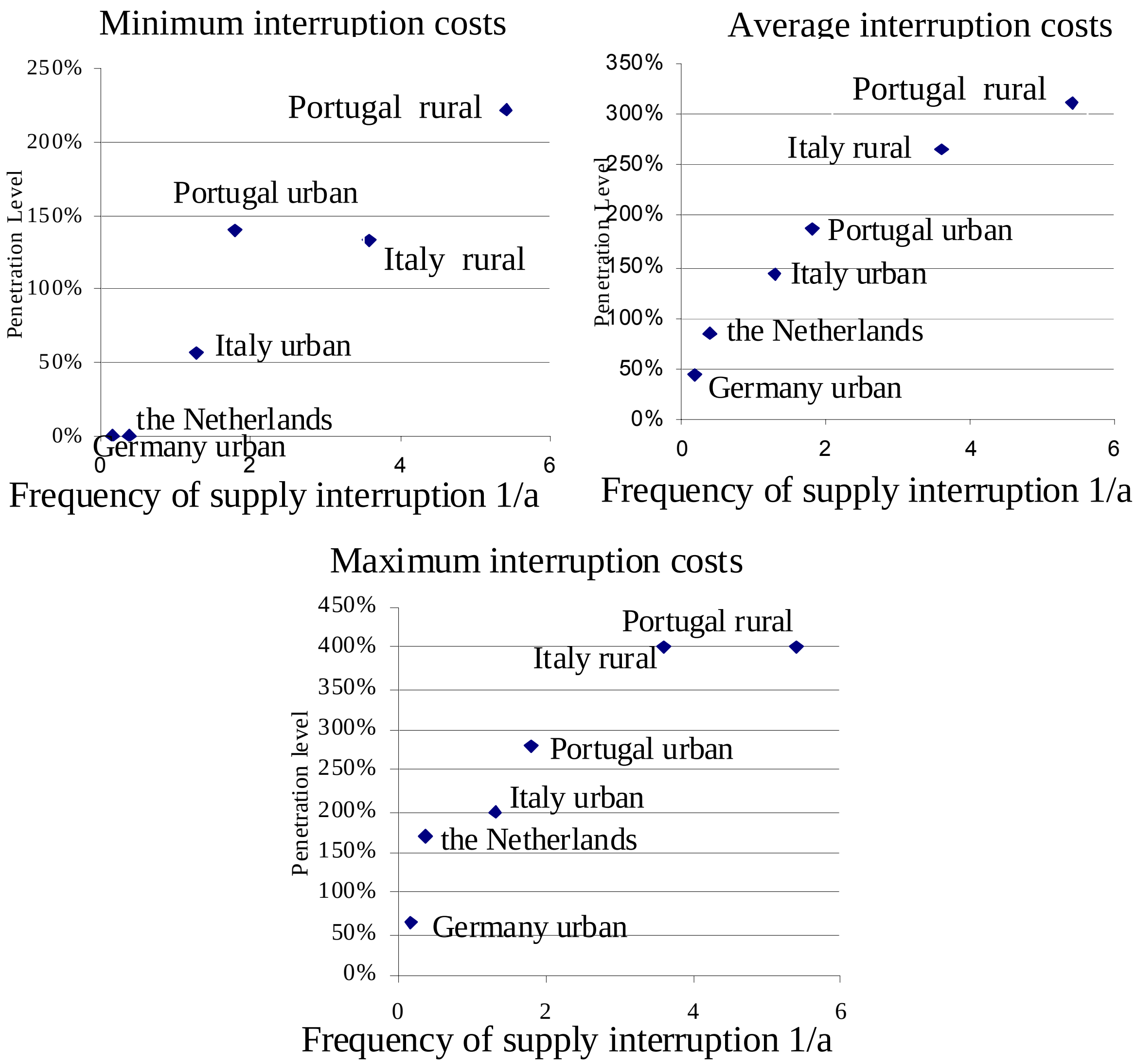


Figure 2-14 Optimum DG Penetration for Minimum Interruption Frequency

Optimum Micro-Source Location

Investigation as described in Annex 4 turned out that, when only failures caused by LV network are considered, optimum micro-source location should take into account the following criteria:

- DG is distributed to different protection zone
- DG is located most downstream in the network
- DG is connected to the load with higher demand
- DG is prioritised to connect with the sensitive load

When failures on MV and HV level (as is the reason for most outages) are also considered, different micro-source locations have the same effect to the reduction of load interruption caused by this failure; micro-sources improve system reliability independent from their location in this case.

2.3 Environmental and Social Aspects of Microgrid Deployment

In Annex 6 of WPG Deliverable DG1, the emission impacts of a Microgrid have been analyzed respectively for greenhouse gases (CO_2, CH_4, N_2O etc.), SO_x, NO_x, and PM (particle matter) etc. Study performed in this Annex reveals that gas-, biomass-, and renewable-dominated Microgrids all have significant potentials in GHG (greenhouse gas) and SO_x reductions in comparison with current emission levels in the electricity sector for most Europe countries, while biomass-dominated Microgrids might experience high NO_x emission levels that are close to mainly coal- or oil-fuelled electricity supply scenarios.

In addition to the general emission reduction via diversification of primary energy sources, Microgrids could also contribute to environmental protection by increasing energy utilization efficiency within the system. Efficiency improvement measures could include use CHP units, DSI to reduce energy consumption, dispatch priority for less pollutant micro-generators, and reduction of energy losses via on-site generation and coordinated DER control etc. Thus, in comparison with passive allocation of renewable and other micro-resources to a distribution grid, a Microgrid can raise environmental performance of the whole system to an even higher level.

When a Microgrid is examined under the context of general society, its influence could easily reach well beyond the power industry and might even eventually change the way of life of many people and redefine the conceptions and habits of even more. A detailed study on social aspects can be found in Annex 7. In short, three major social benefits can be identified from Microgrids:

1. Raise public awareness and foster incentives for energy saving and emission cutting

Due to Microgrids' capability of disseminating DER-created values to end consumers in a network (as shown in section 2.1.2), normal household and commercial participants of a Microgrid will likely to be exempted from increase of electricity price due to feed in tariffs (FIT), or even rewarded by incentive programs if they actually own the RES units or participate in a DSI scheme. This type of economic signal (emission and efficiency values created from a Microgrid will be paid by external entities) can be seen as a strong driving force for acceptance and promotion of Microgrids in the end.

2. Creation of new research and job opportunities

As implementation of a Microgrid requires new knowledge, expertise, and customized hardware and software solutions that are not directly available for both supply- and demand-side players in the market, research institutes and system device manufactures will have to cope with these challenges via creation of new research posts and job openings. In the mean time, new opportunities will be available not just in designing (stereotyping) and installation (standardization) stages, as daily operation and maintenance of a Microgrid will pose real-time metering, communication, and control demands that will formulate new career markets both within and outside of the Microgrid.

3. Electrification of remote or underdeveloped areas

Over a long time, it has been widely acknowledged that DER units are extremely suited for electrifying remote or underdeveloped regions that are either too uneconomic to be interconnected to a nearby distribution grid or simply lacks basic electric infrastructures and finds no power grids in vicinity at all [35]. The Microgrid concept provides a platform for aggregating isolated sectors of self-sufficient households or communities (based on very few micro-generators and storage units) into a more robust network with better balancing and control capacity. Reliable and affordable supply of electricity via Microgrid can be seen as a critical step for modernization and industrialization of local economy.

3 Market and Regulatory Settings for Microgrids

3.1 Internal Market Settings for Microgrids

The internal market of a Microgrid refers to ownership and business models established in between major stakeholders such as local consumers, DER units, DSO, and energy supplier. The nature of a Microgrid's internal market will mainly determine the amount and direction of cash flows within as well as which entity will step up to participate in external market as representative of the whole group of stakeholders. The structure of internal market, however, does not necessarily hold deciding impact on the choice of Microgrid operation strategy or its collective behaviour when examined from external grid; thus two Microgrids with completely different ownership properties might behave very similarly to each other in the external financial market, and the opposite can also be true.

In order to identify the impact of asset ownership on financial interactions among various Microgrid stakeholders, cash flows in internal financial and service markets need to be clarified based on different auditing perspectives. In order to avoid potential confusion over economic terms used in this section, a classification list is given in Table 3-1 to extinguish economic entries that can lead to increase or decrease of a stakeholder's net balancing value, using the cash flow entry's nature (i.e. within a stakeholder, or between two stakeholders, or indirectly caused by another entry) to differentiate various cases.

	Internal source (invisible)	External source inside Microgrid	External source outside Microgrid	Indirect Source (shadow value)
Value Increase	Gain	Revenue	Sale	Benefit
Value Decrease	Cost	Expense	Purchase	Loss

Table 3-1 Clarification of Cash Flow Terms Used for Microgrid Internal Market Analysis

In Figure 3-1, a sample cash flow within a Microgrid is shown to illustrate the use of economic entries listed in Table 3-1. Notably, the difference between derived benefit and basic cost will reveal net value in a transaction, which is the total of all individual profits.

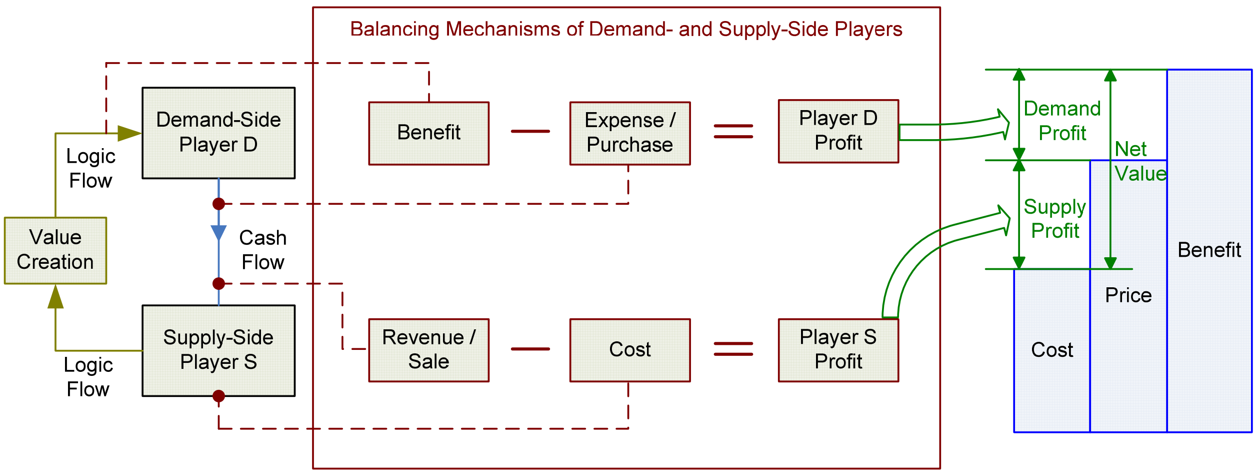


Figure 3-1 Economic Balancing Scheme for a Sample Supply-Demand Scenario

One central message delivered from Figure 3-1 is the possibility of decoupling internal Microgrid pricing decisions from the identification of Microgrid benefits and costs—i.e. all internal transactions within a Microgrid can be seen as only relevant to the allocation of individual profits and thus hold no impact over the amount of created total net value. It is however up to the remaining part of this section to verify validity of this assumption when examined under complicated financial and service markets within a Microgrid.

The differences among various Microgrid structures can be mainly explained as the level of internal liberalization or aggregation: internal makeup of a Microgrid could range from a mere collection of independent market players to a uniform coalition that encompasses almost all demand- and supply-side entities that are either physically or financially involved.

Similar to the case of unbundling between central generation and transmission network, operation right of a Microgrid will be mainly decided by the ownership of Micro-Sources (MS). Thus four general conditions could happen, as shown by Figure 3-2: DSO owns MS, end consumer owns MS, MS operate independently as IPP (Independent Power Producer), energy supplier own MS.

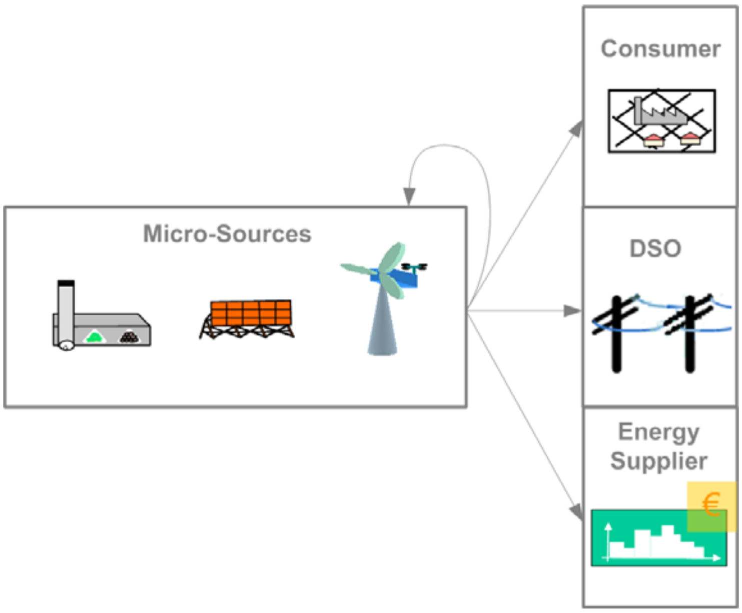


Figure 3-2 Sample Micro-Source Ownership Possibilities in a Microgrid

Although theoretically there could be numerous forms of Microgrids, in reality three typical setups are most likely to occur—which are respectively named as DSO Monopoly, Prosumer Consortium, and Free Market models. Following sub-sections will be dedicated to them.

3.1.1 The DSO Monopoly Model

Obviously, a DSO Monopoly type of Microgrid has very probably evolved from a non-liberalized power industry where DSO not only owns distribution grid but also assumes the retailer function of selling electricity to end consumers. Under this single-player context, integration and operation of DER units are most conveniently undertaken also by DSO, which leaves almost all technical and financial consequences (i.e. both costs and benefits) of Microgrid conversion to DSO responsibility. Thus the DSO assumes an unchallenged monopolistic operator role here, as shown by Figure 3-3.

In a DSO Monopoly Microgrid, DER tend to be larger, and storage units tend to be located at substations.

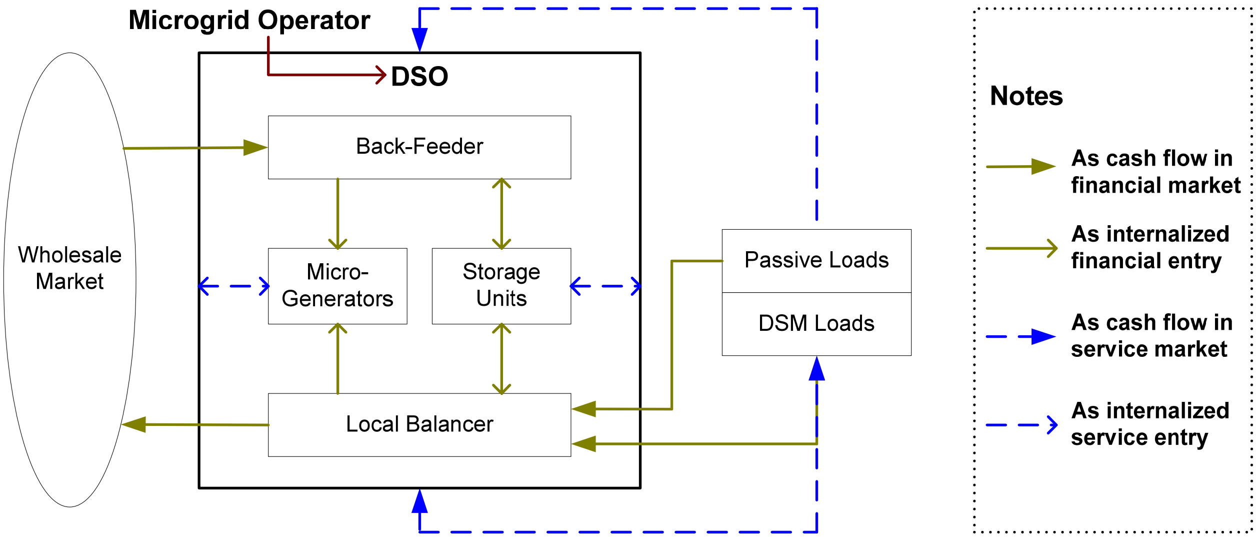


Figure 3-3 Graphical Illustration of DSO Monopoly Microgrid Model

With the business model proposed by Figure 3-3, a versatile 'big' DSO assumes the role of both physical and financial bridges between overlaying grid and end consumers. As DER control decisions are basically made within the framework of DSO functionalities, there will be literally no room for local service market except for potentially tariff-driven DSI programs.

In general, a DSO monopoly Microgrid is mostly likely to be built upon a technically challenged distribution grid with aging, maintenance, and/or supply quality problems. The investment decision in MS units by a DSO (if allowed by market regulator) can be generally explained as an alternative to more expensive solutions to existing network problems (such as replacing overloaded lines to overcome thermal constraint). The potential profitability of selling MS energy to local consumers may or may not turn out to be an initial consideration; but once local value of MS energy is recognized properly, DSO will be very likely the sole beneficiary of such benefits. End consumers, on the other hand, may or may not be informed of the fact that they are consuming local MS energy and consequently have very slim chances of benefiting from Microgrid operation.

3.1.2 The Prosumer Consortium Model

A Prosumer consortium Microgrid (shown by Figure 3-4) is most likely to be found in regions with high retail electricity price or high MS financial support levels (and both conditions are very likely to occur simultaneously). In this case, single or multiple consumer(s) will purchase and operate MS units to minimize electricity bill or maximize sales revenue from MS export (if export tariff is high). This type of Microgrid may find considerable barriers set by DSO, as by nature the consortium tends to minimize the use of distribution grid (which leads to a reduction of UoS revenue) and may neglect all network constraints (i.e. hosting capacity) during design of the Microgrid. DSO can only passively influence the operation of a Prosumer consortium Microgrid via imposing requirements and charges upon the MS owners, but will not be able to benefit from the local trading process.

In a Prosumer consortium Microgrid, DER tend to be smaller, storage tend to be small and dispersed (esp. plug-in electric vehicle).

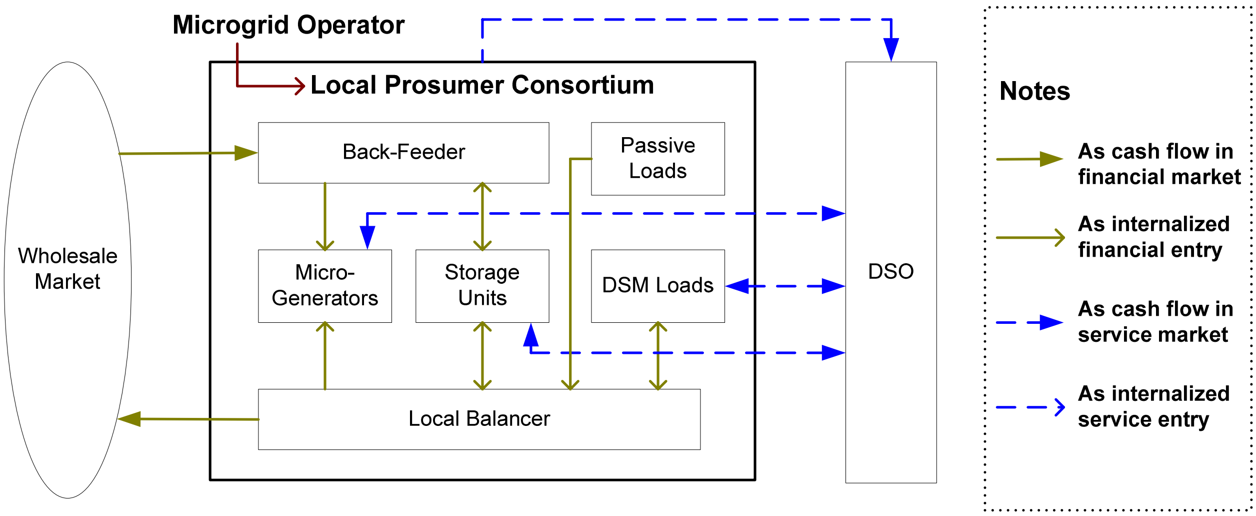


Figure 3-4 Graphical Illustration of Prosumer Consortium Model

3.1.3 The Free Market Model

Finally, a free market Microgrid (shown by Figure 3-5) can be driven by various motives (economic, technical, environmental etc.) from various stakeholders (DSO, consumer, regulator etc.). And the daily operation decisions will be dependent on real-time negotiations (i.e. interest arbitration) of all involved parties. In this case, a Microgrid Central Controller (MGCC) will be present to behave as an energy retailer that is simultaneously responsible for local balance, import and export control, technical performance maintenance, as well as emission level monitoring. The potential benefits of Microgrid operation will be thus splitted and directed to proper recipients on a level-playing basis.

In a free market Microgrid, DER and storage can vary in forms, sizes, and locations.

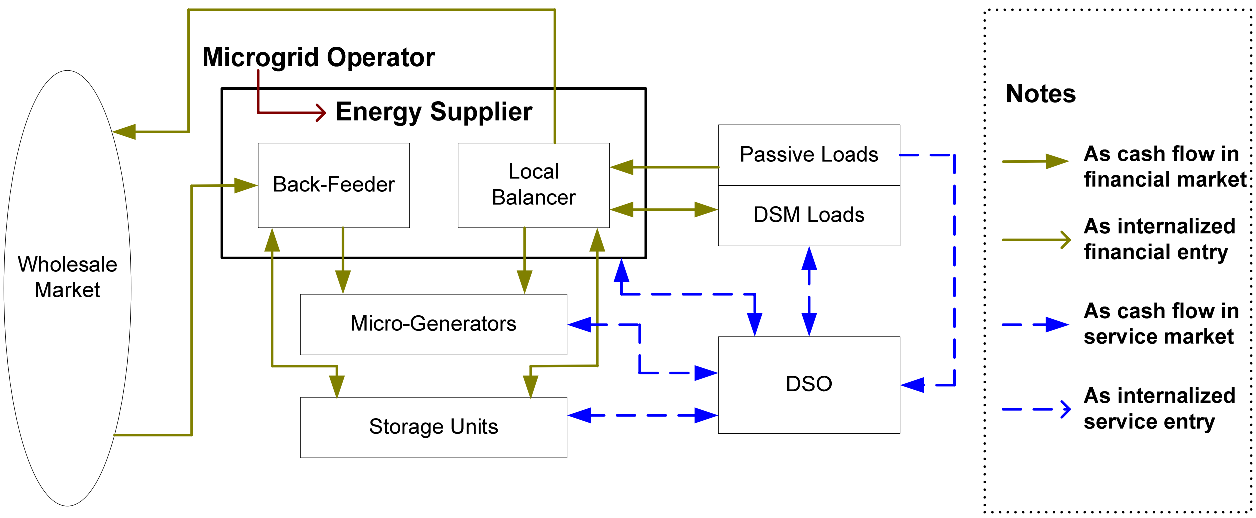


Figure 3-5 Graphical Illustration of Free Market Model

3.1.4 Costs and Revenues for a Microgrid Operator

Despite individual differences, for all three examined ownership models, a common target value can be defined as:

To Minimize: Target Value = Self Supply Cost – Export Profit (if applicable)

- **Self Supply Cost = Import Energy Cost + MS Generation Cost for Self Supply**
- **Export Profit = Export Sales Revenue – MS Generation Cost for Back-Fed Energy**

This target value can be understood as the sum of opportune costs minus opportune revenues obtained from optimal real-time dispatch decisions between internal (MS) and external (market) resources. Of course, for each Microgrid ownership model examined, extra internal cost entries will arise due to the differences of corresponding interest allocation models. A more detailed illustration of interest allocation among introduced Microgrid stakeholders is presented in deliverable DH3.

3.2 External Market and Regulation Settings for Microgrids

One critical influence factor on the financial and technical feasibility of Microgrids is the market and regulation settings applied from external environment. As all investment decisions are de facto based on projected profitability, the external environment of a Microgrid will hold major impact over whether or not a commercial-level Microgrid will come into existence. In the mean time, the adaptability of public policy for Microgrid to constant technological evolution will also prove to be critical for creating a level playing field for both existing and new players in the market.

There are two major aspects of external influence over a Microgrid: pricing scheme and technical expectation. Pricing scheme refers to the setting of how buying and selling of electricity is handled between Microgrid and external grid; it can be characterized by four main criteria:

(1) Acknowledgement of local consumption;
(2) Directional (buying and selling) pricing difference;
(3) Time dependency of Microgrid price;
(4) Financial incentives such as feed-in tariff (FIT).

Technical expectation means the potential aspect of operating a Microgrid as a (quasi) predictable, dispatchable, and controllable component to the upstream network, which substantiates the possibility of ancillary service provision from Microgrid (as a whole) to overlaying system operator but could also turn out to be an economic discouragement due to extra metering, communication and control costs.

3.2.1 Visibility of DER Generation and Recognition of Local Consumption

As already discussed in the introduction section, one key implication of Microgrid concept is the promotion of a local retail market in an either transparent or implicit manner so as to diversify end consumer choices. This local retail potential, however, can be seriously challenged by existing structure of power distribution and retail business, especially when DSO and/or retail energy supplier view high Micro-Source penetration as a threat and exercise their market powers to formulate discriminatory terms to compel MS out of competition, or at least create sufficient barriers to enhance their own stance if they cannot shun away from the establishment of a local retail market.

Depending on the level of retail liberalization and unbundling, a Microgrid could face the five levels of treatment in terms of utility acceptance.

(1) Complete Hostility

- Grid connection of MS is strictly banned.
- Demand Side Integration (if any) is not recognized or accounted for.
- Retail monopoly or switch of retailer is not feasible.

(2) Passive Tolerance

- MS are allowed to be connected to grid only if they cause no reversal of power flow—in case that reversed power flows do occur, they are expected to be small, short, non-critical, and most importantly not remunerated in any sense.
- Demand Side Integration may be encouraged in word or paper, but no tariff or incentive programs are implemented.
- Retail competition may exist between several energy suppliers, but none of them are aware of MS existence or hold any ownership or trading relation with them.

(3) Fit and Forget

- MS are freely allowed to connect to grid; back feeding is allowed and remunerated at wholesale price level as long as they cause no major technical problems (overloading, voltage, protection etc.). No aggregation of any form exists as penetration level is low.
- Demand Side Integration measures based on no-cost (e.g. voluntary energy reduction) or low-cost (selection of water pump operation time) nature are practiced and suitably awarded.
- Retail competition exists, majority of retail suppliers have experience with buying from MS electricity, which, however, only account for a small share of their energy portfolios.

(4) Micro-Source Aggregation

- MS penetration reaches a considerably high level to be able to aggregate multiple units to an energy output level eligible for wholesale market participation. The aggregation operator could appear in form of VPP or a raw Microgrid without demand integration.
- Demand Side Integration incentives from both consumer side (e.g. efficiency and energy saving) and supplier side (e.g. time of use retail tariff) are responded with good acceptance, DSI values are recognized and well compensated for.
- Retail competition exists. One or more energy suppliers in a region consider aggregated MS as an important alternative to central generation, some even try to purchase operation or ownership rights over certain MS units.
- MS and load follow separate cash flows with no inter-crossing.

(5) Demand Integration

- MS aggregation optimizes its operation to compete against central units in a local retail market so as to win over end consumers.
- Demand Side Integration is performed with a systemic sense, where information transparency and availability are greatly improved to spread know-how among all players. Demand controllability reaches a very high level.
- Retailer function is integrated as a part of Microgrid operator’s duty.
- Operational aim is not simply to ensure MS profitability or effectiveness, the load side, MS side, and grid side interests are considered as a whole to optimize the performance of the complete system.

The evolution from level 1 to level 4 can be also seen as general development of Micro-Source units in LV grid. Concurrent DSO attitudes toward Micro-Sources and Microgrids are mostly clustered around level 2 and level 3, leading to maximum MS penetration level of 15% to 30% in a potentially ideal market environment [36]. Further regulatory and financial supports could stir up MS penetration level beyond 50% to 100% or even more in LV grids by step 4, but such a grid does not necessarily become a standard Microgrid.

The key step of evolution towards Microgrid implementation is the conversion from level 4 (Micro-Source Aggregation) to level 5 (Demand Integration) model, which represents a fundamental regulatory reform in the conceptual design of LV distribution system in terms of local consumption acknowledgement.

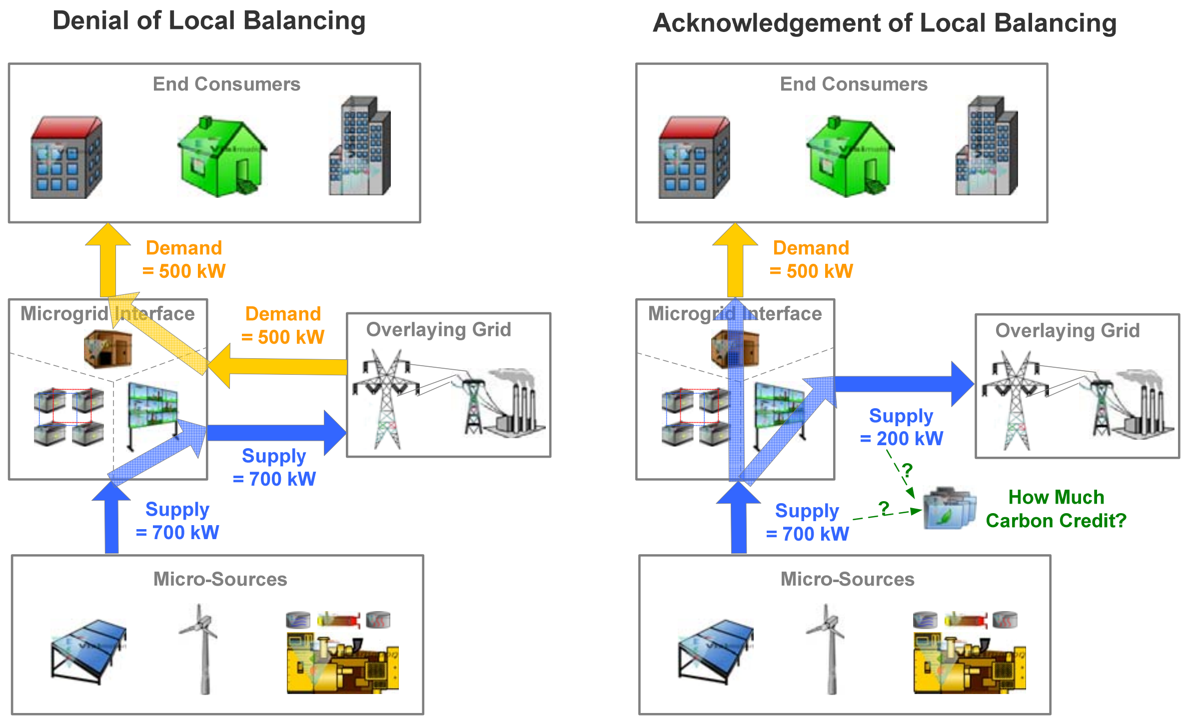


Figure 3-6 Impact of Local Balancing

Acknowledgement of local consumption (explained by Figure 3-6) appears to be a default setting for small amounts of consumer-owned MS units where 'Passive Tolerance' (level 2) philosophy generally applies, which is true as long as no power flow reversal happens and no separate metering of MS generation is required. Once on-site generation and on-site load are metered separately and MS units start to appear as independent generators that are not financially owned by any end consumer, local consumption will be the easiest 'shadow' market opportunity that can be overlooked by all players—either consciously or not.

The main purpose of promoting local consumption acknowledgement within a Microgrid is twofold: (1) to equip end consumers with more buying power in terms of retail choice, (2) to grant MS units with the possibility of obtaining quasi-retail prices via selling locally to minimize network charges. The local market retail concept is therefore directly linked to the local consumption mechanism, which can also be seen as a two-sided hedging tool for both demand and supply players for reducing market risk: consumers could use the local market to hedge against high market price, while MS could use the local market to hedge against low market price (further details to be covered in section 3.2.2).

There is a serious potential risk, however, that could incur from the local consumption concept: when MS units of different technologies in a Microgrid are remunerated with different tariff mechanisms—e.g.: RES units that enjoy fixed FIT prices and natural gas CHP units that might be compensated by wholesale market price with a certain premium on top—then if local generation exceeds local demand, it will be questionable as to which MS units contribute to local supply and which units contribute to the exported energy. Obviously, a Microgrid operator is needed here to arbitrate the settling of buying and selling prices within a Microgrid to ensure impartial interest allocation to all players in the field. This is discussed further in section 3.2.4.

3.2.2 Impact of Directional Pricing and Exemption of Use of System Fee

A Microgrid operator is likely to face power trading with external grid on an everyday basis, which implies both purchase and selling of electricity that could either be coupled with interface power flow (local trading acknowledged) or not (local trading denied). This makes a Microgrid somehow comparable to a 'Prosumer' industrial client with on-site generation that is connected to HV level. There is however one big difference between a Microgrid and a HV Prosumer: HV Prosumer can buy and sell at similar wholesale price levels with negligible or no network charge applied on power import, while a Microgrid is likely to be faced with wholesale price for export and (quasi) retail price for import if no regulatory intervention applies to the current distribution and retail sector.

The described directional pricing scheme for a Microgrid can be mainly explained by the application of network charge or Use of System (UoS) charge on top of basic electricity price in wholesale market. However, it is quite natural to argue that a Microgrid should not be required to pay all the traditional transmission and distribution UoS charges for internally consumed energy as this part of power flow only circulates within the small LV grid. Since MS units that do not enjoy a fixed FIT would normally lack competitiveness against large central units due to economics of scale, exemption (total or partial) of UoS fee can eventually justify profitability of these MS units via addition of positional value.

Therefore, if nothing can be done about the directional pricing for trading between a Microgrid and external grid, then at least acknowledgement of local energy consumption could make it possible for end consumers and MS units to trade at mid-level prices in between wholesale and retail level, which could result in economic benefits for both sides. Thus whether or not local consumption is acknowledged can be a critical index of Microgrid profitability under directional pricing at external interface.

On a further note, when political and social support for Microgrids reaches a sufficiently high level, system operators may agree to retract some of their UoS charges imposed on power trades between Microgrids and external generators or loads—especially when power deficit or power surplus from one Microgrid can be met by another one, or by a DG or controllable load located at MV level. The basic reasoning behind this idea is to extend the internal consumption concept of a Microgrid to Multi-Microgrids – the aggregation of Microgrids in conjunction with MV level DG and controllable loads that are comparable in size with a complete LV Microgrid In this way (shown by Figure 3-7), selling and buying prices both within and outside of a Microgrid can be unified to promote bi-directional trading on a real-time basis.

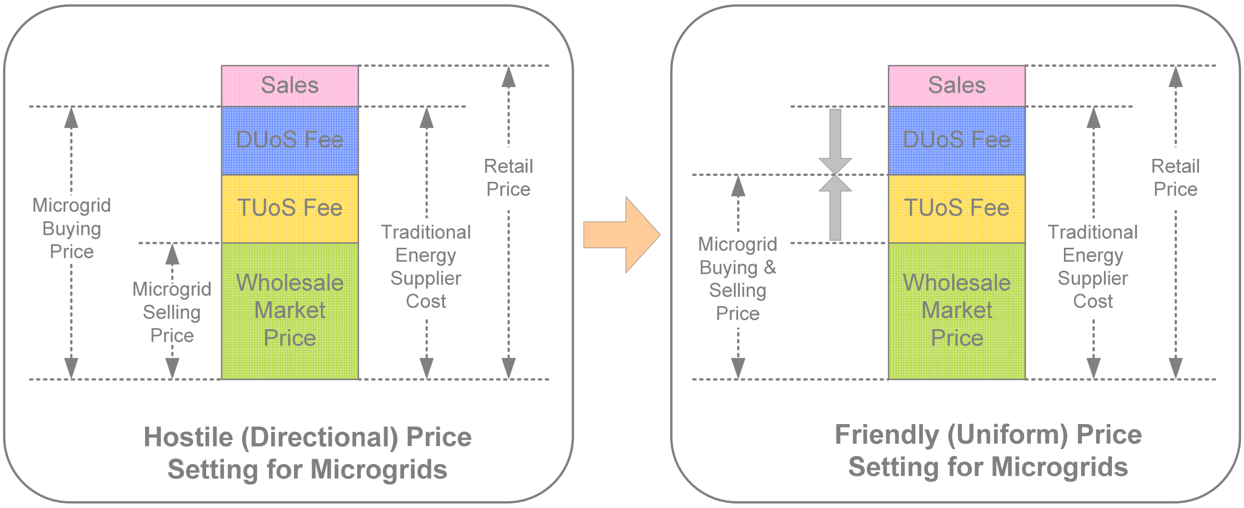


Figure 3-7 Price Settings for Microgrids

One noticeable fact concerning uniform pricing scheme is that acknowledgement or denial of local energy consumption no longer holds any financial consequence over the profitability of a Microgrid. As the gap between power import price and power export price disappears, the chance for striking an internal middle price is also gone; and a more transparent trading platform will be consequently formed for both internal and external players. It should be noted, however, that by uniform pricing scheme the local retail market does not simply disappear, it is actually merged with other similar small scale local markets to form a larger regional market.

In summary, when local consumption recognition and setting of buying and selling prices are considered as a whole, three general levels of Microgrid support can be expected:

(1) Hostile: Directional Pricing + Denial of Local Consumption

(2) Neutral: Directional Pricing + Acknowledgement of Local Consumption

(3) Friendly: Uniform Pricing + Local Consumption Always Acknowledged

Since the hostile case places MS at the same competition level as central units and denies any local value created by them, the most likely starting point for a Microgrid is the neutral case where internal and external markets with asynchronous price settings coexist. The friendly case (i.e. ideal citizen behaviour) will become possible when dissemination ratio of Microgrids in a MV grid reaches a sufficiently high level so as to enable Multi-Microgrid operation. In addition, the neutral treatment case has the potential of creating a ‘forced’ economically islanded Microgrid (i.e. good citizen behaviour, as shown by Figure 3-8), which will be detailed in section 3.2.3.

In the end, it should be noted that while the term ‘exemption of UoS fee’ apparently implies a transfer of opportune revenue from TSO or DSO to MS or end consumer, in reality the cash flow does not necessarily follow this standard route. The exempted cost could eventually be paid by end consumers that are outside of considered (Multi-) Microgrid, or by potential investors of new central generator units, or by all players that could obtain opportune profit from application of such a fee etc.

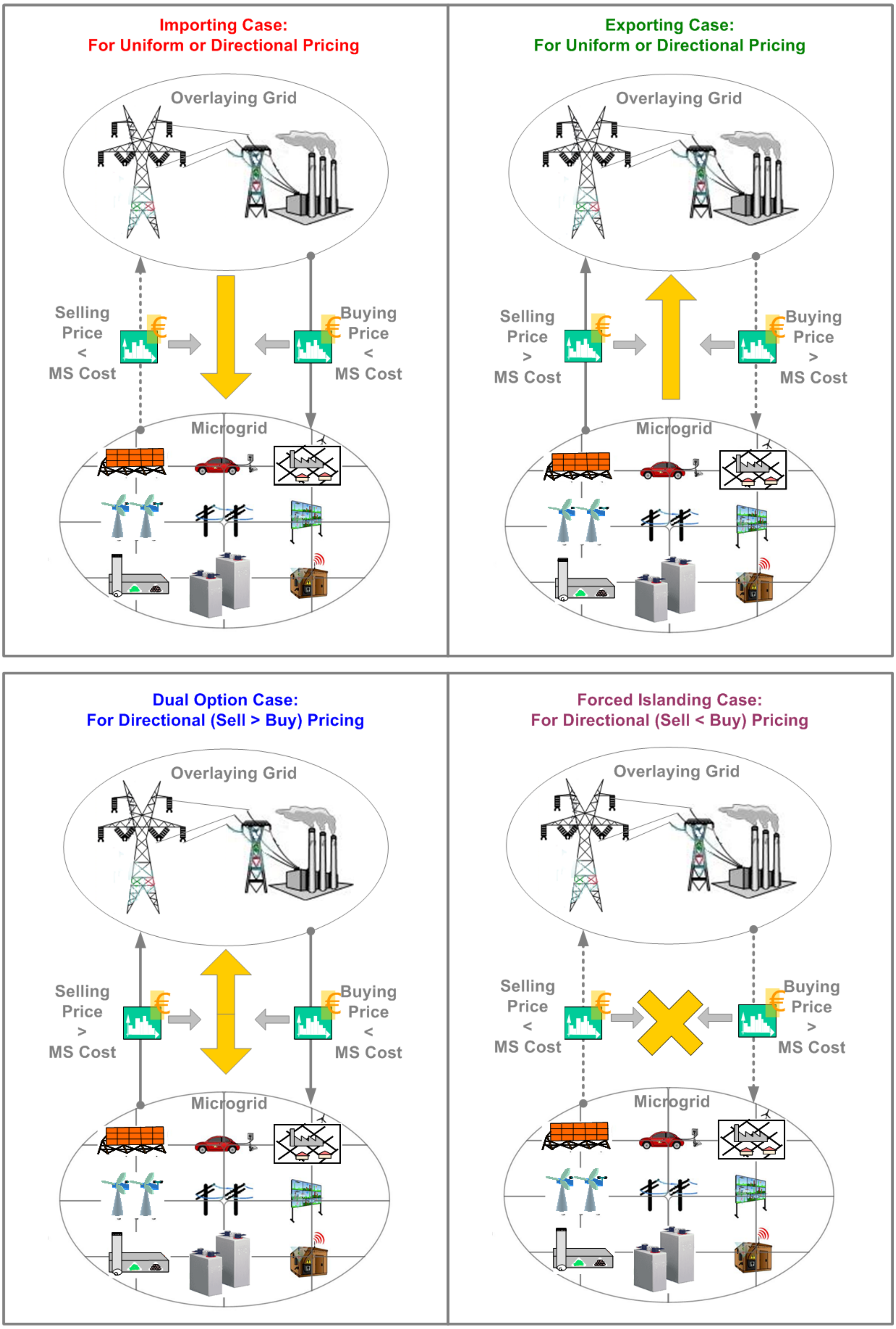


Figure 3-8 Correlations between Microgrid Power Flow and Price Settings

3.2.3 Impact of Microgrid Tariff: Constant and Real Time Options

When it comes to the topic of time-domain characteristics of Microgrid tariff, two aspects can be generally included: external trading price between Microgrid and external grid as well as internal trading price between MS and end consumers. As the latter value only relates to interest allocation within a Microgrid (thus belongs to the content of DH3 report), only the first (external) price will be considered in this section, for which two levels of pricing flexibility are assumed:

- Constant price: a Microgrid obtains a constant selling price and a constant buying price (under uniform pricing scheme both prices converge) for participation in external energy market.
- Real time price: a Microgrid obtains hourly (or sometimes on 15 minutes scale) prices for both selling and buying electricity (per standard wholesale market behaviour).

In between these two options, a Time of Use (ToU) price can also be adopted as follows: an on-peak price and an off-peak price are cycled for each day; when seasonal power variations are distinct, a second set of on- and off-peak prices can be applied to winter and summer periods. This ToU setting is generally seen in DSI programs where peak shaving or load shifting effects are expected. For the purpose of Microgrid study, however, it can be simply viewed as a simplified version of real time tariff.

Firstly, the constant pricing scheme is most likely to be introduced to mini-scale Microgrids on building or community level where real-time measurement is either absent or fails to provide sufficient details on both demand- and supply-side power flows. Despite its relative convenience of implementation, the constant pricing strategy can lead to three types of situations in response to aforementioned price setting schemes:

(1) Under hostile pricing environment (Directional Pricing + Denial of Local Consumption), the constant market buying price can be literally below the basic cost of all available MS technologies, thus preventing any Microgrid formulation in the first place even though potential profits from peak support do exist.

(2) Under neutral pricing environment (Directional Pricing + Acknowledgement of Local Consumption.), a Microgrid is likely to consist mainly of MS technologies that feature generation costs in between selling (wholesale) and buying (retail) market price levels. This means it will be uneconomical for a Microgrid to buy any deficit or sell any surplus as long as local demand can be met by local generation—this effectively turns a Microgrid into (quasi) island operation even if a physical connection to external grid does exist in reality.

(3) Under friendly pricing environment (Uniform Pricing + Denial/Acknowledgement of Local Consumption), any Microgrid that is economically feasible to build will behave as a maximum exporter with all MS units geared towards maximum output at all conditions—as once MS units are aware that they can sell for profit under all times, they will show totally no load responsiveness and care nothing about local interest at all.

It is interesting to observe that a constant pricing scheme can lend too much market power to central generators when combined with a hostile environment for Microgrids, and similarly grant MS units with too much market power when combined with a friendly pricing environment for Microgrids. Both cases will eventually undercut total system efficiency. The only situation that could potentially justify its application is the neutral environment setting, where the Microgrid is 'forced' into an economic island in which both MS and end consumers could get better off than simply selling to or buying from external grid. This economic island mode, however, can also be viewed as an external attempt of minimizing power exchange requirements from a Microgrid or as a direct consequence of market power exercised upon Microgrids.

With application of real time pricing, however, again three situations could occur as follows:

(1) Under hostile pricing environment (Directional Pricing + Denial of Local Consumption), only the cheapest MS units with comparatively large sizes (e.g. gas turbines) will be seen in a Microgrid and they only function as peak-supporting units with relatively low utilization rates.

(2) Under neutral pricing environment (Directional Pricing + Acknowledgement of Local Consumption), a MS unit in Microgrid could potentially have three operating states: <1> when MS cost is below instantaneous selling (wholesale) price, the MS will behave as maximum exporter, <2> when MS cost falls in between selling (wholesale) and buying (retail) prices, the MS will follow local load as if in an economic island, <3> when MS cost is above instantaneous buying (retail) price, the MS will simply shut down. The ratio of these three states depends on market price volatility, gap between buying and selling prices, as well as MS cost range. And the instantaneous condition of the Microgrid could consist of one or multiple of these operating states.

(3) Under friendly pricing environment (Uniform Pricing + Denial/Acknowledgement of Local Consumption), a Microgrid can be viewed as a combined economic optimizer that simultaneously attempts to minimize opportune cost for end consumers (by choosing the cheaper source between MS and external market) as well as to maximize opportune profit for MS units (by selling most profitable amounts of energy according to real time price in merged power market).

Obviously, the hostile pricing environment can only lead to a minimum raw Microgrid with no local retail market at all. The neutral pricing environment, when combined with real time prices, could lead to the complicated co-existence of two hourly settled power pools both within and outside of a Microgrid, which in consequence might introduce three operating states for individual MS units and six operating states for the whole Microgrid. In comparison, friendly pricing environment under real time setting leads to a much more transparent and easy to implement economic framework with merged internal and external markets, which can be viewed as the ideal market setting for a Microgrid.

In short, there are potentially three general price settings that can lead to Microgrid adoption, namely they are island, hybrid, and exchange cases, as shown by Table 3-2.

	General Environment	Time Domain Setting
Reference Case	Hostile: Directional Pricing + Den. Local Cons.	Constant Pricing
Island Case	Neutral: Directional Pricing + Ack. Local Cons.	Constant Pricing
Hybrid Case	Neutral: Directional Pricing + Ack. Local Cons.	Real Time Pricing
Exchange Case	Friendly: Uniform Pricing + Ack. Local Cons.	Real Time Pricing

Table 3-2 Definition of Different Microgrid Price Setting Schemes

Graphical Example for Impact of Microgrid Price Setting Schemes

In order to illustrate the potential economic consequences of the four proposed pricing scenarios, a four-hour, two-unit dispatch problem is analyzed with the following assumptions:

Mean wholesale price is assumed to be 7.5 ct/kWh, mean retail price is assumed as 13.5 ct/kWh. Unit MS1 is rated at 30 kW with 12 ct/kWh, unit MS2 is rated at 15 kW with 15 ct/kWh. Hourly demands are assumed to be 15 kWh, 35 kWh, 25 kWh, and 5 kWh from hour 1 to 4.

In Figure 3-9, market prices and MS costs (represented by cost indices *k*) are plotted as lines, while real time active power (represented by *P* indices) dispatch results from MS units and external market (positive as import, negative as export) are plotted as blocks.

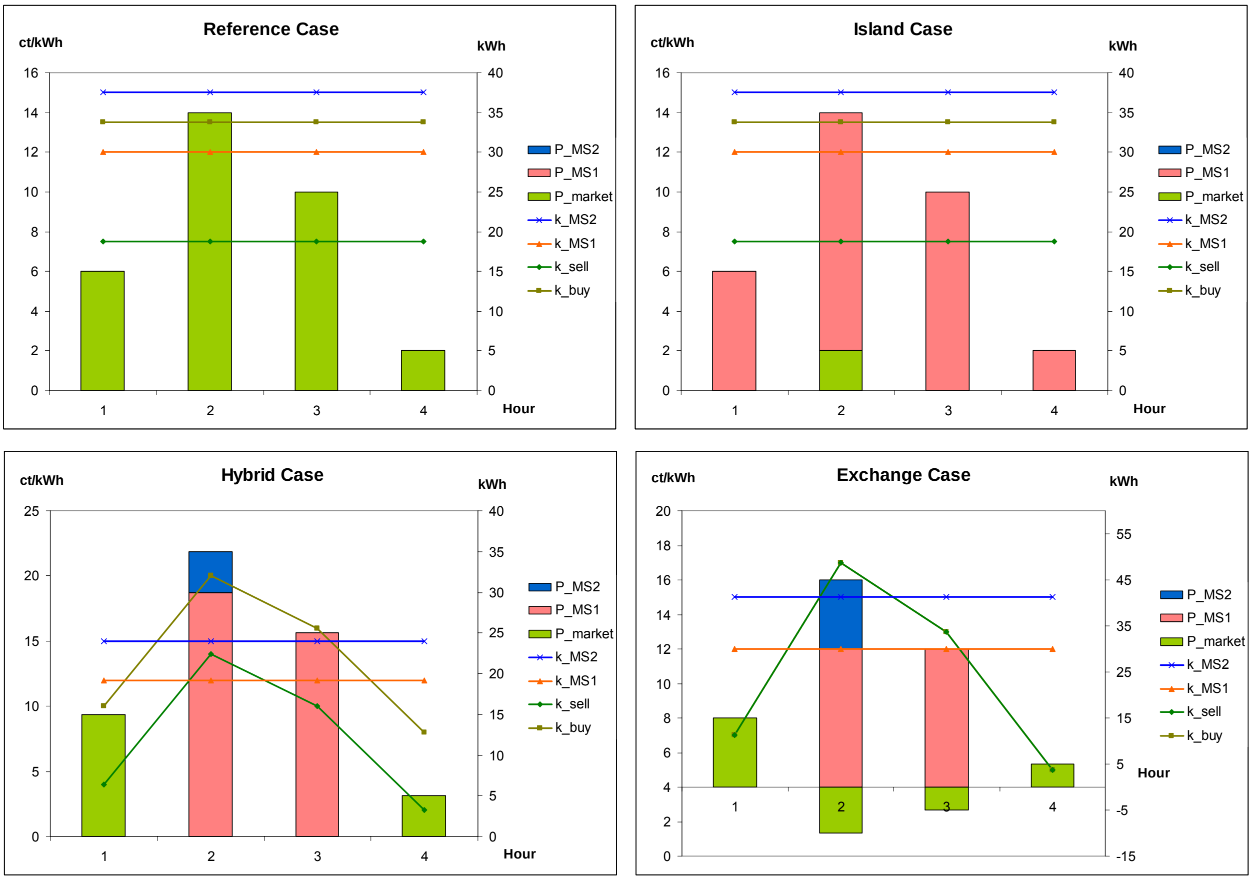


Figure 3-9 Sample Illustration Case for Microgrid Pricing Settings

The price and power diagrams in Figure 3-9 indicate that a Microgrid will import all demands under reference case (thus zero MS utilization); while under island case it will attempt to be self-sufficient with the most economic MS unit(s) available. Both hybrid case and exchange case try to use the cheaper source of power (market and MS units) at each instant, but the hybrid case tends to discourage export of excess MS generation (due to directional pricing) while the exchange case creates a favourable pricing environment for bi-directional trading.

In Figure 3-10, per kWh electricity costs in the sample Microgrid are compared for the four scenarios: obviously the cost goes down as price flexibility and transparency improves. The exchange case is now financially proven to be the truly ideal situation that can be created for a Microgrid as it minimizes total social cost for electricity supply within the system. The (forced) island case can be seen as the minimum requirement for establishment of Microgrids, while the hybrid case switches between island and exchange modes following variations of real time prices.

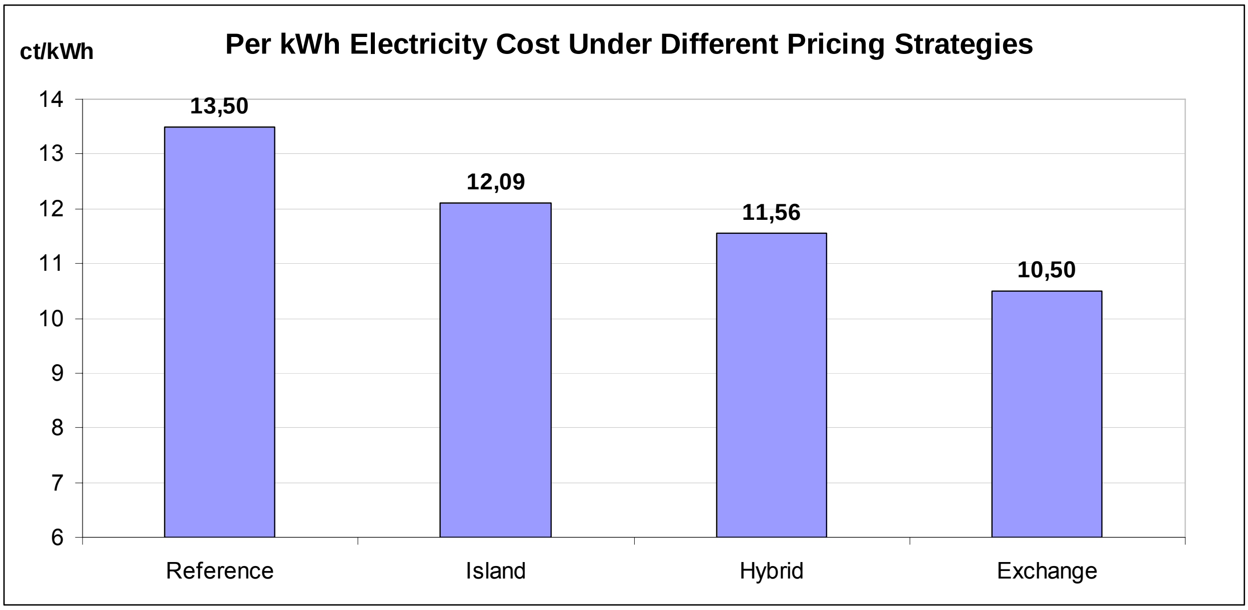


Figure 3-10 Costs under different Pricing Strategies

It should be noted that the sample case suggests large MS capacity that even exceeds peak load demand so as to create possibilities of excess generation for export; if the MS units in a Microgrid are too small to achieve reversal of power flow, the eventual cost difference between island and hybrid case could be reduced significantly—in some cases the island case may even lead to lower costs than hybrid condition. Considering the comparative complexity of dual-market implementation and corresponding costs, the hybrid solution is apparently quite challenging to implement despite its conspicuous advantage (only small regulatory changed needed compared to exchange case) when used as a starting point market setting for Microgrids.

3.2.4 Potential Financial Incentives Needed for Microgrids

Up to now, all discussions within section 3.2 are based on dispatchable MS units with basic generation cost comparable to quasi-retail price level. Within a Microgrid, however, there are likely small RES units that are intermittent in nature (thus not load-responsive) and have generation cost far above retail price level (thus not price-responsive). In this case, financial or regulatory support schemes are required to ensure profitability of these RES units so as to create a level playing field for all MS technologies.

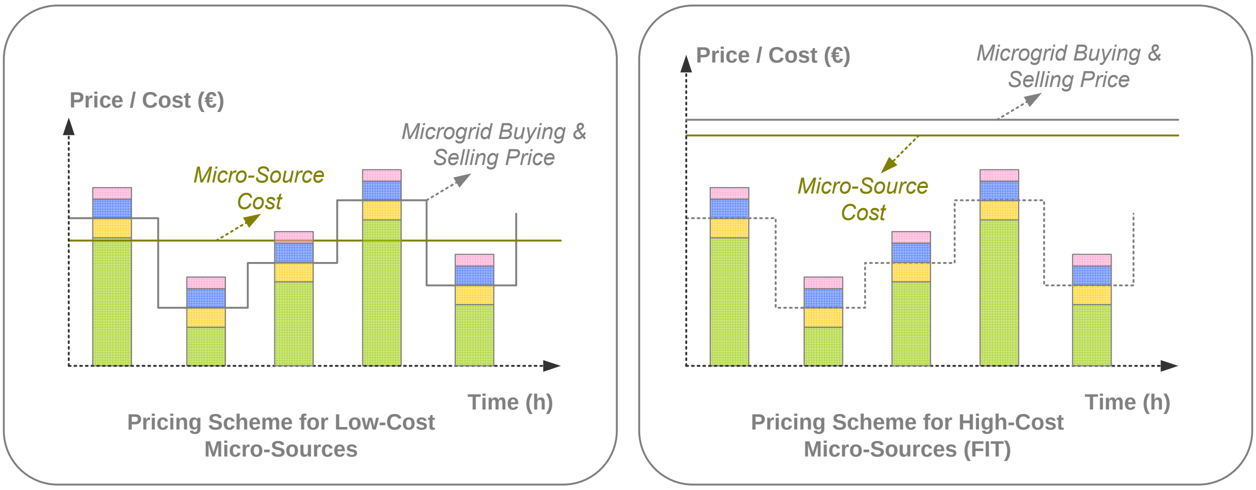


Figure 3-11 Prices and Costs of Microgrid Operation

As quota-based renewable obligation systems are basically not concerned with financial consequences of the installed units, in scope of this report only the financial incentive options are examined, namely feed-in-tariff (FIT) and premium systems. The FIT system applies a (seasonally or annually modified) constant purchase price (normally above average wholesale level) for a given type and size range of MS technology, while the premium system adds a constant bonus on top of time-varying wholesale market price for the specified MS technology.

For intermittent RES units (PV, wind turbine, small hydro), as fuels are normally not required and operation and maintenance costs mostly fall below base load market price, it is generally not economically or environmentally favourable to dispatch the unit (in sense of limiting unit output or shut down the unit) unless unsolvable technical problems would arise without intervention. In this light, adoption of FIT and premium systems will lead to the same always-on operation philosophy as any watt-hour not sold is simply wasted, regardless of whatever price level is adopted for the moment.

For dispatchable RES units (mainly biomass), CHP units (bio- or natural gas fuelled), and emerging technologies (e.g. fuel cells), financial incentives might still be needed so as to bring unit cost closer to quasi-retail (friendly pricing) level. With these dispatchable units that are susceptible to fuel consumption, application of FIT and premium systems will lead to a major behaviour difference: any dispatchable MS units under FIT will attempt to yield maximum output at all times, while premium system will cause the same units to show a much more price-responsive commitment pattern.

Obviously, for an 'economic island' Microgrid with fixed buying and selling prices, choice between FIT and premium systems will not have any impact on MS operation pattern. For Microgrids under ideal 'exchange' environment, application of constant FIT to dispatchable units could potentially undermine total system efficiency as these units with guaranteed time-invariant profit margin could exercise too much market power in the local grid.

Thus under ideal (i.e. uniform, real time pricing) market and regulatory setting, all dispatchable MS units should be included in a financial incentive program that works under premium rather than FIT philosophy. As for intermittent RES units, both FIT and premium systems could apply, as eventual MS profitability will be similar any way.

3.3 Provision of Ancillary Services by Microgrids to Overlaying Grids

A number of authors (i.e. [9], [12]) have pointed out that with concurrent tariff structure and hostile pricing environment, the most likely profiting opportunity for a Microgrid is to participate in the ancillary service market. This suggestion is generally based on the argument that MS units are unlikely to obtain sufficient competitiveness against central units in wholesale power pool if their emission, efficiency, and locational benefits are not recognized in financial terms—thus instead of serving as standby or peak-supporting units with slow investment return, a more reliable source of income can be expected from MS participation in ancillary service market, in which more chances are available for relatively smaller and more expensive generators.

In general, Microgrid involvement in ancillary service market can be categorized into two types: real power related and reactive power related services.

(1) Real power or frequency related services

Depending on response speed, MS units in a Microgrid could potentially offer to control their active power output (which in effect excludes all intermittent RES units) so as to take part in a frequency regulation, spinning reserve, or supplementary (non-spinning) reserve service market. In general, all these active power related services require a reduction of MS output below rated level or even complete shutdown of the unit to serve as backup reserve in case of emergency situation.

The basic idea behind Microgrid participation in balancing or reserve market is to get higher prices than general wholesale level, which is similar to the concept of creating a local retail market or to exempt some of UoS fees imposed on MS-generated electricity. Assuming a local retail market exists in parallel to wholesale power pool, then the better tariffs in balancing or reserve market might come at the price of foregone opportune revenue if the MS unit can get a better deal by selling to local consumers during peak demand periods. On the other hand, a MS unit could get extra revenues from reserve market almost for free by staying at hot standby state when market prices in both local and external markets are below its basic generation cost.

There are two critical problems, however, related to the potential recognition of Microgrid as a supplier of balancing or reserve service:

Problem 1: If local consumption has been acknowledged and Microgrid is treated as a Prosumer by overlaying grid, then frequency or active power responsiveness of the whole Microgrid will be determined by the synergy of local load and local generation. This means under an emergency situation, promised operation reserve (+/–) from dispatchable MS units might be consumed first by variations of local load or RES units before it could reach to external grid. In an extreme case with massive intermittent RES penetration, a Microgrid could become a consumer of balancing and reserve powers rather than a supplier of them.

Problem 2: As a Microgrid with sufficient MS penetration level will be very likely to be designed to feature islanding capability in case of main supply loss, it will be an operational dilemma during grid disturbance as to if maintaining grid-connected operation or conversion to island mode should be the first priority. In case a technical border line can be clearly defined for decision to turn into island mode, financial complications might ensure as to if the frequency (or active power) support services prior to islanding should be remunerated at all.

Therefore, it might be difficult for a Microgrid to get recognition for balancing or reserve service as a whole as it will be quite impractical to control the complete Microgrid to show similar balancing or standby behaviour as a standard central generator. However, dispatchable MS units should be able to serve local loads and RES units directly as a source of balancing and reserve power, negating or reducing their potential charges that would otherwise have to be paid to external generators.

(2) Reactive power and voltage related services

The idea of providing reactive power service or voltage regulation service from a Microgrid to upstream network is generally based on a ‘good citizen’ behaviour [7], in which Microgrids are expected to cause minimum problem to overlaying grid or even to export reactive power balancing service or to perform voltage control at infeeding point to support upper-level system operation. The potential problems associated with reactive power and/or voltage control services are similar to the issues encountered by active-power related counterparts, namely they are:

Problem 1: Under a conservative and non-transparent regulatory setting, upstream network operator tends to apply the reactive power regulation and voltage control requirements as mandatory requirements rather than potential technical service entries upon a Microgrid. In this case, Microgrids are not able to be remunerated via active control of reactive power sources within to meet technical standards imposed by external authorities.

Problem 2: In case a Microgrid does get proper recognition for supplying reactive power to upstream network, its Prosumer identity will force it to have a sufficiently large MS penetration level and potentially over-designed reactive power capacity from both RES and dispatchable MS units so as to create net export of reactive power when load demand is high.

Consequently, although reactive power or voltage control to upstream network does not potentially hold a high probability of interfering with optimal internal economic dispatch of MS units as provision of active power-related services do, chances are still high that a Microgrid either does not meet up with the basic requirement of reactive/voltage service provision to upstream network, or does not receive proper recognition (i.e. remuneration) when it actually qualifies for the service entries.

As a summary, in scope of this study, Microgrid’s provision of ancillary service to upstream network is considered as a plausible but insecure source of income, which is subjected to a large variety of uncertain impact factors from both internal and external sources. Therefore, it should be already sufficient to examine the potential technical benefits of Microgrids at local (i.e. inside Microgrid) level, which can of course propagate proportionally to upstream networks as Microgrid dissemination ratios in MV grids increases to sufficient levels to form Multi-Microgrids.

4 Control Elements and Control Strategies of a Microgrid

4.1 Controllable Elements and Models for Microgrid Components

As already discussed in section 1.2, a minimum Microgrid should at least consist of both demand and supply resources as well as the carriers of physical power flow (DSO) and financial cash flow (energy supplier). On top of this basic requirement, a Microgrid could potentially contain energy balancing forces such as dispatchable loads, E-cars, and substation storage units (Figure 4-1) that could either contribute to minimization of power exchange (in case of economic or physical island) or maximization of power arbitrage profit (in case of free exchange under friendly pricing condition). In scope of this section, the physical natures as well as control and management guidelines for these (potentially) controllable units are explored as a consequence.

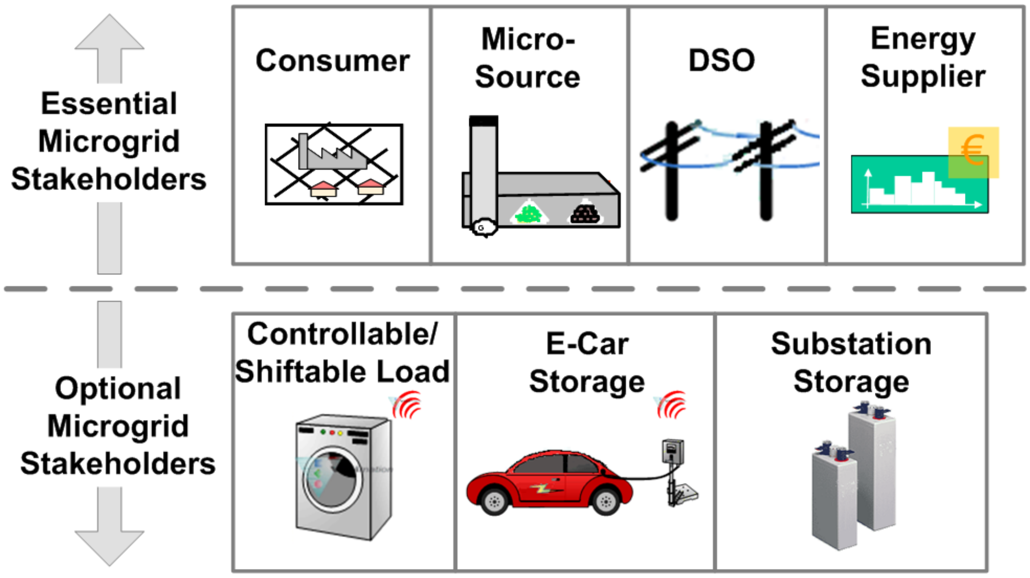


Figure 4-1 Microgrid Stakeholders

4.1.1 Intermittent RES Units

Intermittent RES units are the most likely form of micro-source that will be expected to appear in a Microgrid—some times even to the extent of dominating a Microgrid due to political support or environmental concern. Typical intermittent RES unit in a Microgrid can be a photovoltaic array, a micro wind turbine, or a micro hydro power plant. Although tidal and wave energy sources are also considered to be intermittent in nature and applicable to Microgrid scale, they are too location-limited and currently expects no fixed prospect for large scale commercial application.

Among listed intermittent RES options, photovoltaic technology is undoubtedly the most flexible source of renewable power that can be installed at a great variety of locations and appear in a large range of sizes with minimum maintenance requirement. Currently, it is also widely acknowledged to be among the most expensive generation technologies available for a Microgrid. This cost disadvantage, however, might gradually vanish in future due to the extremely fast reduction of its production cost over the recent decades (in comparison with other MS technologies). Major limitation for its adoption in Microgrids in future might therefore change from panel cost to inverter, control, and communication costs, especially for small systems (< 5 kW).

Wind turbines, on the other hand, prove to be the most popular RES technology in recent years due to its relatively low cost and maintenance needs. The potential room for wind turbines in a Microgrid, however, is rather limited in comparison with PV, as the majority of wind turbines produced nowadays is above MW rating and is normally aggregated into wind farms that are in consequence interconnected to MV or HV grids with sufficient transport capacity. Micro wind turbines (rated typical at several tens to hundreds kilowatts) that are more suited for Microgrid application have generally been overlooked simply due to economics of scale. However, recently rising interests in community generation might rekindle manufacturer's interest in micro wind turbines.

Finally, micro hydro power plants are typically run-of-water applications that are quite susceptible to seasonal and annual weather patterns. Although it is generally considered to be a location-limited technology, total penetration level of small hydro units in a certain region could easily aggregate into a dominating force inside a Microgrid, thus special attention has been paid to small hydro applications within this report.

In terms of economic, technical, and environmental aspects, intermittent RES units can be described as follows:

- Concurrent micro-scale RES units generally lack financial competitiveness in terms of cost per kWh generated electricity (especially PV), thus direct economic incentives or obligatory quota systems will be needed to promote their adoption.
- Active power output from all intermittent RES units is subject to one or multiple environmental force(s) and is thus neither fully predictable nor dispatchable (at least in positive regulation direction). Reactive power output from RES units with properly designed power electronic interfaces, however, can be adjusted independently from available active power level and can be seen as a controllable source in a Microgrid.
- As GHG and other forms of emissions from renewable power sources can be seen as minimum or negligible, intermittent RES units should be dispatched with highest priority in terms of environmental concern.

As a summary, controllability of intermittent RES units is simultaneously limited by the physical nature of primary energy source, financial pressure from high investment cost, as well as environmental concern over return of carbon emission (i.e. from production stage). Consequently, it is generally not advisable to dispatch intermittent RES units unless they are causing severe line stress or over-voltage problems—as any watt-hour that is not fed from intermit RES unit into grid is simply wasted (negligible fuel cost), leading to a lost opportune carbon credit and a lost opportune sales revenue.

The control strategy for intermittent RES units can be therefore described as follows: all intermittent RES units are generally excluded from the normal unit commitment schedule as long as they do not breach system constraints, while all units with independent reactive power interfaces (decoupled from active power output) can be included in a reactive power dispatch scheme to improve technical performance of total Microgrid.

4.1.2 Dispatchable MS Units and CHP Operation

Aside from intermittent RES units, all other forms of MS generators within a Microgrid can be described as dispatchable or quasi-dispatchable units that generate power roughly in proportion to overall fuel consumption. This fuel dependency, together with specific costs associated with unit switching (on/off), will economically determine the controllability of a dispatchable MS unit in response to market price variations (if applicable). Therefore, this second category of MS units is mainly featured by flexibility of unit output (both real and reactive power outputs) as well as unit switching state, which makes them the main source of controllability within a Microgrid.

Due to environmental concerns, the majority of fuels consumed inside a Microgrid will appear in form of natural gas, bio-fuel (biomass, bio-gas, and bio-diesel etc.), and solar thermal energy (geothermal resources are typically too location-limited for Microgrid applications). Hydrogen might turn out to be an alternative if proper storage and transport routines could become available, although no large-scale adoption has been potentially foreseen before 2030. In the mean time, eligible technologies for dispatchable MS units mainly include Microturbines (5-100 kW), small gas or steam turbines (100-1000 kW), fuel cells (50-1000 kW), as well as Stirling engine based solar thermal units with heat storage (5-20 kW).

It should be noted that aside from turbine-based and fuel cell technologies, there are also potential prospects in terms of using reciprocating engines (mainly internal combustion type) as dispatchable MS units. The problem with reciprocating engines, however, mainly lies in its combustion efficiency, air emission, and noise level, which makes it difficult for them to uphold a general efficient and clean image for a Microgrid. Thus concurrent market is mainly open for turbine-based technologies, while solar thermal units mainly rely on renewable financial incentives for project profitability and fuel cells are expected to enter large scale commercial application around 2030 or later.

As literally all dispatchable MS units applicable for Microgrid operation involve a heat-to-electricity conversion process, there are basically always possibilities of utilizing the residual heat from this energy conversion link to achieve combined heat and power (CHP) operation. Depending on specified location and configuration, a CHP unit could operate under either fully electricity-driven (in case thermals storage or district heating network exists) or fully heat-driven (in case the unit supplies an islanded heat load such as a single building) mode under normal network conditions.

In order to simplify analysis scenarios, it is assumed in this report that all fuel-based MS units (if applicable) in a Microgrid will be operated under CHP mode, and that all bio-fuel based CHP units within a Microgrid will be heat-driven (thus considered similarly as intermittent RES units) and all natural gas-fired CHP units will be heat-driven (thus considered as dispatchable micro-sources). Under emergent conditions—i.e. loss of main grid, however, all CHP units are assumed to be instantly switched to electricity-driven mode to support grid stability.

In terms of economic, technical, and environmental aspects, dispatchable MS and CHP units can be described as follows:

- Currently, gas-fired turbine generators (cheapest available option) in Microgrid scale are only economically feasible for peak-power support if they are forced to compete against central units in the wholesale market. Their shares are expected to grow tremendously if their locational (i.e. local retail), environmental (i.e. lower emission), and/or efficiency (i.e. CHP operation) values can be recognized in explicit (direct premium) or implicit (formation of local retail and emission market) financial manners. Bio-fuelled MS units and fuel cells, on the other hand, require separate incentive programs to compete against other technologies at the moment.
- As all dispatchable MS units are expected to operate under CHP mode, their controllability varies according to how they are supposed to meet local heat demand: (1) when heat demand far exceeds MS output capacity, the unit is fully controllable in electrical terms; (2) when heat demand is comparable to MS output and an intra-day heat storage unit is available, the MS unit will be partially controllable as long as total daily output satisfies daily heat demand; (3) when heat demand is comparable to MS output and no storage is

available, MS unit output will fully follow local heat profile. Since MS units are generally based on rotating machine units, reactive power output capacity will be constrained by both active power output and apparent power rating.

- In general, bio-fuelled MS units can be seen as the most favourable option for maximizing environmental benefit of a Microgrid. However, in case of resource limitation (esp. in highly populated urban areas) or logistical problem, natural gas appears to be the second-best choice due to its lower emission content over other fossil fuels. Solar thermal and hydrogen powered units, if available, can be classified as renewable resources with good controllability and enjoys highest environmental priority among dispatchable MS units.

Due to improved controllability and price- or load-responsiveness of dispatchable MS units, a Microgrid with multiple MS units of different sizes and technologies will be eventually faced with the traditional unit commitment problem—albeit under a much smaller scale. The Microgrid operator, however, need to cope with much higher net load variations (i.e. load minus intermittent RES output) but generally faster unit response time (negligible ramp rate and relatively short cool-off time under hourly time frame). In the mean time, optimization constraints will likely include grid operating states as well as emission targets, which add much more complexities to the unit commitment task on top of traditional part-load unit efficiencies.

4.1.3 Storage Units

It has been generally assumed that storage units are only needed for Microgrids that intend to operate under island mode—which is true as long as storage usage cost stays above the potential revenue from arbitrage in the power market. In addition, compulsory storage requirements might be imposed on a Microgrid to limit the variations from its instantaneous power import or export. This in general leads to two potential storage applications within a Microgrid:

(1) Balancing storage units that are either technically operated to offset power variations or economically operated to maintain minimum cost island operation;

(2) Arbitrager storage units that participate in power market by exploring the price differences between on-peak and off-peak periods during a day.

Obviously, a balancing storage unit is operated with (net) load-following characteristics, while an arbitrager storage unit shows distinct price-following characteristics. At the current stage of Microgrid development, neither option appears to be capable of justify initial investment in pure economic terms—unless, of course, the Microgrid is a physical island without any main connection (or too remote to have economic main connection). Nonetheless, storage units are also expected to make their appearance in Microgrids with grid connection even before their costs are reduced to a commercially profitable level, which can be mainly expected from technical (power quality requirement) or environmental (maximize local RES consumption) concerns.

Depending on size and location of unit, storage applications within a Microgrid can be also classified into centralized and decentralized types.

Centralized storage units are normally installed at transformer substation or infeeding node of a Microgrid, which is in general expected to be invested by DSO to maintain a certain level of technical performance from the Microgrid, which can be mainly translated into power balancing applications of both short-term (second to minute level) and long-term (hourly level) natures. With sufficient unit rating, however, centralized storage units can become a major contributor of dynamic support and frequency regulation during loss of main supply or long-term island operation.

Decentralized storage units, on the other hand, are normally expected to be dispersed over the whole Microgrid in a similar pattern as micro-generators. Despite disadvantages from economics of scale (similar to MS units), decentralized storage units might eventually become an unstoppable trend with the advent of plug-in hybrid vehicles and plug-in electric vehicles (E-cars)..

In the end, storage units can also be defined according to adopted technology, which means both battery and non-battery applications can be expected in a Microgrid.

Considering space and civic engineering requirements, battery is by far the most widely applicable storage option for both centralized and decentralized units in a Microgrid. Concurrent research activities are mainly focused on lead acid, nickel metal hydrate, and lithium ion batteries: lead acid battery is generally the cheapest and the most mature solution available, but it suffers from environmental impact from lead material and a comparatively short cycling life; nickel metal hydrate, on the other hand, could offer good power and energy performances with relatively safe and durable operation, but high cost and maintenance requirement currently prevents it from wider adoption; lithium ion batteries generally have the best loading capacity and lifecycle performance, but it suffers from safety concerns and currently has the highest overall system cost.

Apart from batteries, storage demand from a Microgrid can also be met by the following technology options: pumped hydro, compressed air energy storage (CAES), fly wheel, and super capacitor. The former two (pumped hydro and CAES) options are generally location-limited with considerable space requirement, but once available they could provide sufficient capacity for maintaining long-term islanded Microgrid operation. The latter two options (flywheel and super capacitor), however, are generally much smaller in energy content, thus normally they are short-term (second to minute level) balancing units for RES or standby reserves used for emergency state frequency regulation.

In terms of economic, technical, and environmental aspects, battery units can be described as follows:

- None of concurrent storage technologies have reached commercial maturity for power balancing or price arbitrage purpose of application. However, with commercial propellers such as E-car concept, costs associated with storage systems (especially battery) are expected to drop in near future, which could eventually justify third-party investment in battery units within a Microgrid.
- Technically, a storage unit could behave either as load-following or price-following depending on its purpose of operation. In the mean time, storage units based on different technology options can provide balancing reserves ranging from short term (dynamic to minute-level static behaviour) to long term (hourly to daily static balance) applications. Specifically, for DC-based storage technologies (battery, super capacitor etc.), a properly designed power electronic interface could contribute to reactive power balance of the system without incurring significant operational costs.
- Environmental impact of a storage unit consists of two aspects: lifecycle impact and operational impact. The former aspect mainly depends on the storage unit’s scale and technology choice (i.e. water reservoir consequences of pumped hydro and waste metal treatment of exhausted batteries), while the latter one directly links to the energy conversion and storage efficiency (i.e. energy loss due to storage usage) during daily operation of a storage unit.

4.1.4 Demand Side Integration

Demand side integration (DSI) also referred to as demand side management (DSM), demand side response (DSR) or demand side bidding (DSB), is a general summary of end consumer initiative programs for creating win-win situations (for both supply and demand sides) via collective voluntary adjustment of electricity consumption patterns to a profile-changing scale.

Traditional DSI measures are mainly targeted at smoothing load profiles to minimize the necessity of switching on or off central generator units, which can be simply put as peak shaving and valley filling. In a Microgrid, however, overlaying grid and dispatchable MS units are faced with the net balance of local load and intermittent RES output, which in effect means DSI programs in a Microgrid is most likely to be targeted at smoothing the combined power curve from load and intermittent RES rather than load profile itself.

Therefore, instead of rule-of-thumb consumption curtailment or boosting during intuitive ‘peak’ and ‘valley’ hours of a day, DSI measures in a Microgrid have to be made on the basis of forecasted load and RES outputs and will very probably vary from day to day. In comparison with the relative straightforwardness of traditional DSM programs (e.g. use your washing machine at 12 pm instead of 6 pm and save energy bill); Microgrid DSI measures are not easily comprehensible to general public (e.g. use dish washer at 2 am today but at 2 pm tomorrow because wind blows differently) and generally requires unmanned intelligent load control to function properly.

Thus the basic requirement of Microgrid DSI measure is full adoption of smart metering and smart control (if applicable) of household, commercial, and agricultural loads within the Microgrid. Depending on criticality of target load, DSI measures can be generally divided into two categories:

(1) Shiftable load, which refers to a predefined task that can be completed with flexible time schedule in scope of a day. Typical applications include water pumps, electric water heating devices, etc.

(2) Interruptible load, which refers to unessential or constant loads that can be reduced or switched off during supply constraints or emergency situations. Typical applications include standby devices (with no near-term use plan) and day-time lighting etc.

In economic, technical, and environmental aspects, dispatchable loads can be described as:

- Controllable/shiftable load in a Microgrid can fulfil its objective on either a voluntary or compensated basis, while in the latter case remuneration fees could be either drawn from DSO or traded as a service item in the balancing market.
- As an LV load in future could be a normal one, a shiftable one, or an interruptible one in nature, potential ‘smart homes’, ‘smart offices’, and ‘smart farms’ in a Microgrid will correspondingly need to provide three different types of power sockets so as to maximize DSI benefits.
- DSI measures can be seen as an efficiency initiative towards carbon reduction.

4.1.5 Proposed Control and Management Hierarchy

For both off-line planning and on-line operation, a Microgrid operator is very likely to be faced with the task of dispatching a large number of controllable resources of different types—i.e. intermittent RES, dispatchable MS, storage units, and dispatchable loads. In case a central controller or operator does not exist, decentralized agents representing each of these control sources will need to negotiate an operational plan that in effect roughly equals or approaches the central dispatch result.

Obviously, a unanimous treatment of all control sources with same priority could lead to very complicated modelling and optimization requirements. For example, recently there have been a lot of interests over the coordinated commitment of both MS and distributed storage units [37], which, however, might be difficult to implement in reality. This is caused by the fact that storage units have significant time memory effect (can only be optimized along a time axis) and light requirement on multi-unit coordination; while MS units show only weak time memory effect (on/off time duration limits) but exhibit strong multi-unit coordination needs. Integrating control sources of different models into one optimization platform could eventually turn out to be too complicated to justify its potential benefit.

In consequence, it is proposed in this report that the following dispatch hierarchy should be applied to all Microgrids so as to facilitate analysis and physical application:

Normal Load and Intermittent RES -> Dispatchable Load -> Storage -> Dispatchable MS

4.2 Microgrid Operation Strategies

4.2.1 Problem Formulation

Currently available distributed generation (DG) units provide a wide variety of different active and reactive power generation options that can be implemented. The final schemes may depend on conflicting interests among different stakeholders involved in electricity supply, such as system/network operators, DG owners, DG operators, energy suppliers, and so on, as well as customers or regulatory bodies. Optimal production scheduling in Microgrids may thus be based on economic, technical, or environmental aspects (Figure 4-2).

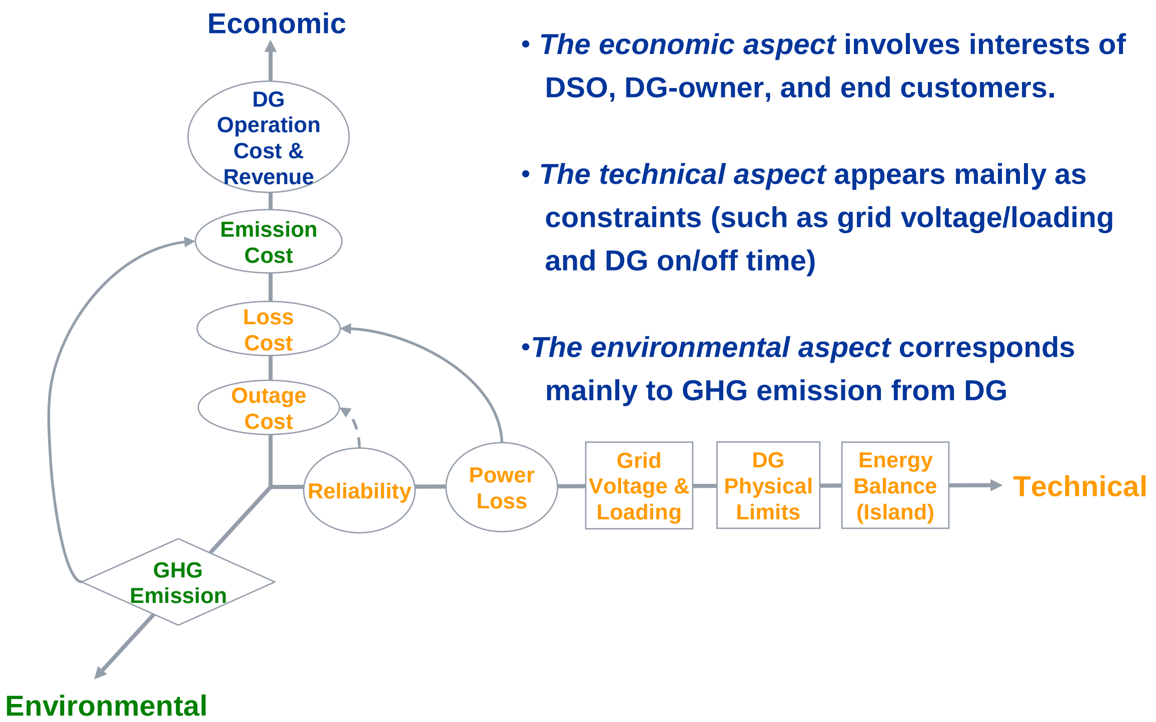


Figure 4-2 Microgrid Operation Strategies

4.2.2 Potential Operation Modes

Depending on the specific stakeholders involved in the analysis, there are different Microgrid operational options that were analyzed and optimised, described as follows.

The objective function in the economic option is to minimise total costs regardless of network impact/performance (Figure 4-3). This option may be envisaged by DG owners or operators, and the Microgrid can also be addressed as a Commercial Virtual Power Plant (CVPP).

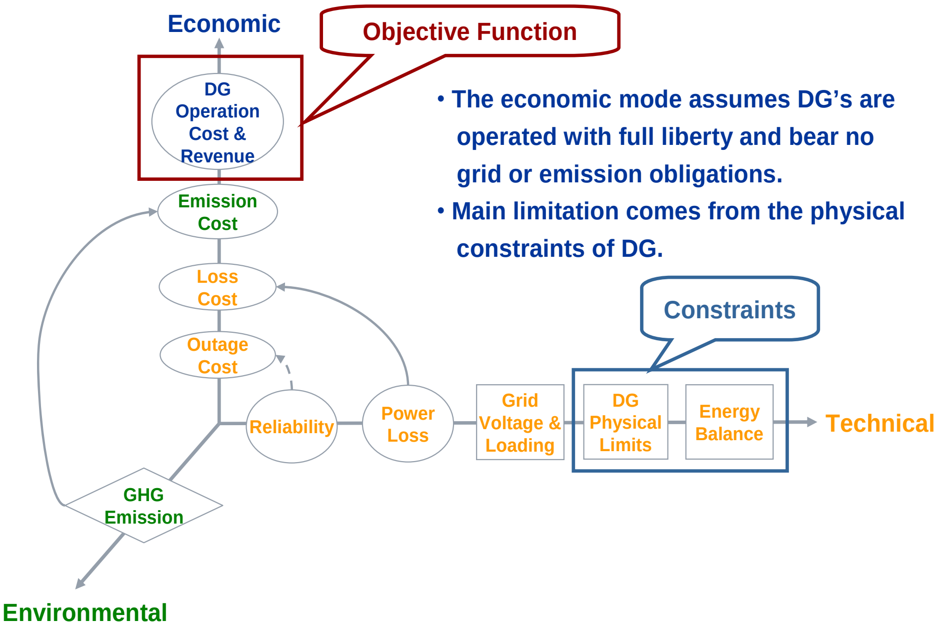


Figure 4-3 Economic Mode of Microgrid Operation

The technical option optimises network operation (minimise power losses, voltage variation, and device loading), while DG production costs and revenues are not considered (Figure 4-4). This option might for instance refer to system operators.

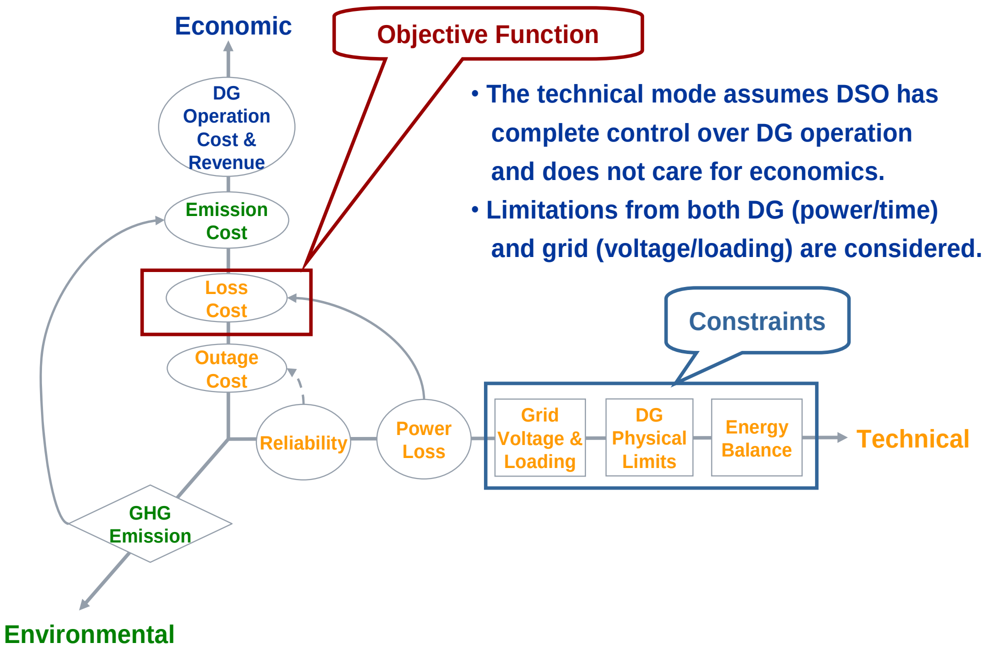


Figure 4-4 Technical Mode of Microgrid Operation

DG units with lower specific emissions are always operated with higher priority under the environmental option, disregarding financial or technical aspects. This is preferred to meet environmental targets, currently mainly supported by regulatory schemes (Figure 4-5).

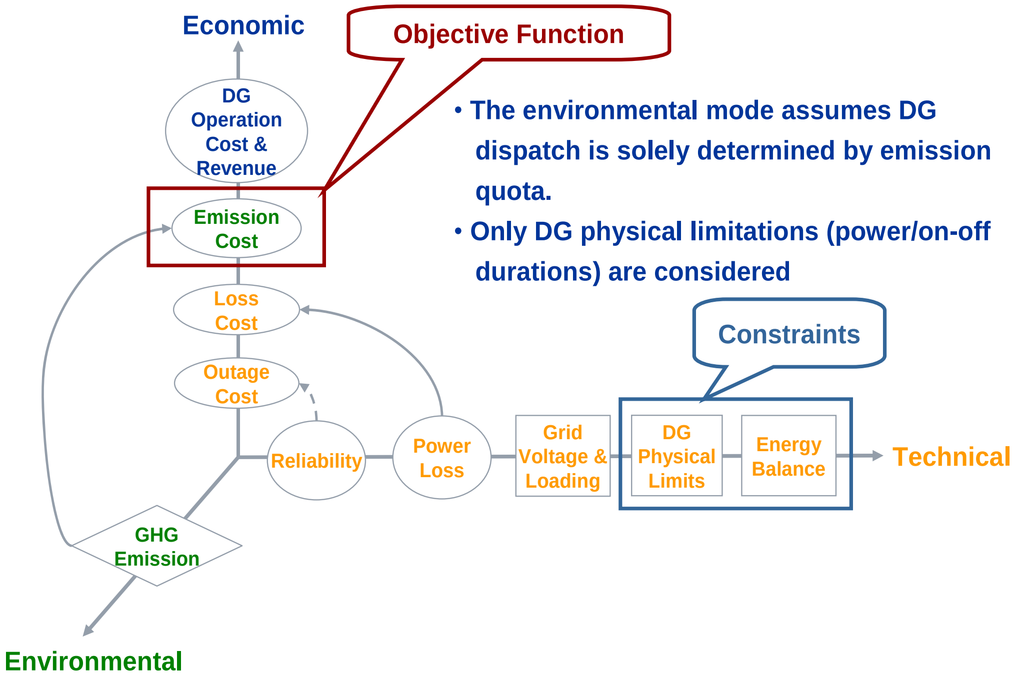


Figure 4-5 Environmental Mode of Microgrid Operation

The combined option (Figure 4-6) includes a multi-objective DG optimal dispatch taking into account all economic, technical, and environmental factors. This approach could be relevant, for instance, to actors within (potential) markets for provision of network services and emission certificates, besides the conventional energy markets.

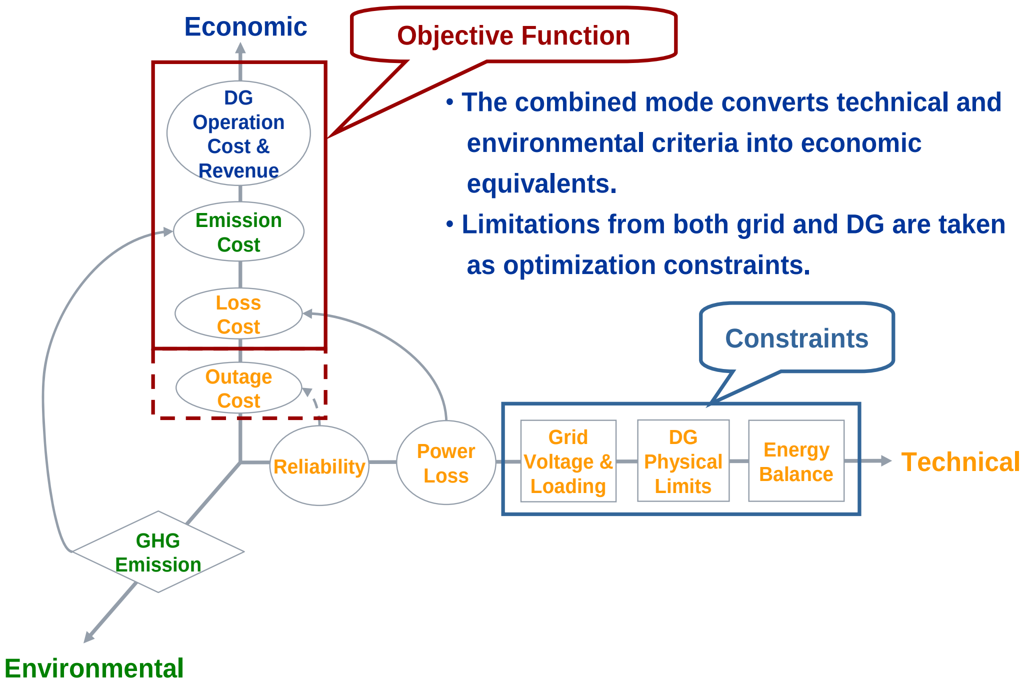


Figure 4-6 Combined Mode of Microgrid Operation

4.2.3 Grid-Connected vs. Islanded Operation

This section aims to provide an answer to the following question: 'what makes it necessary for a Microgrid to operate as an island?' In order to fully comprehend the potential reasons behind island decision, a stepwise analysis is performed in terms of Microgrid locality level.

Firstly, it is necessary to clearly define the term 'island' and 'self sufficiency', as some promoters of Microgrids prototypes (esp. Microgrids without any storage unit) tend to use cumulative annual energy balance as an indicator of self sufficiency and 'quasi' island capacity (Figure 4-7). In terms of carbon credit calculation, this definition can be seen as equivalent to the 'true' island case with zero energy trading in both directions. In terms of technical performance, however, an annually balanced Microgrid could be a far step away from a real island and thus should be excluded from consideration.

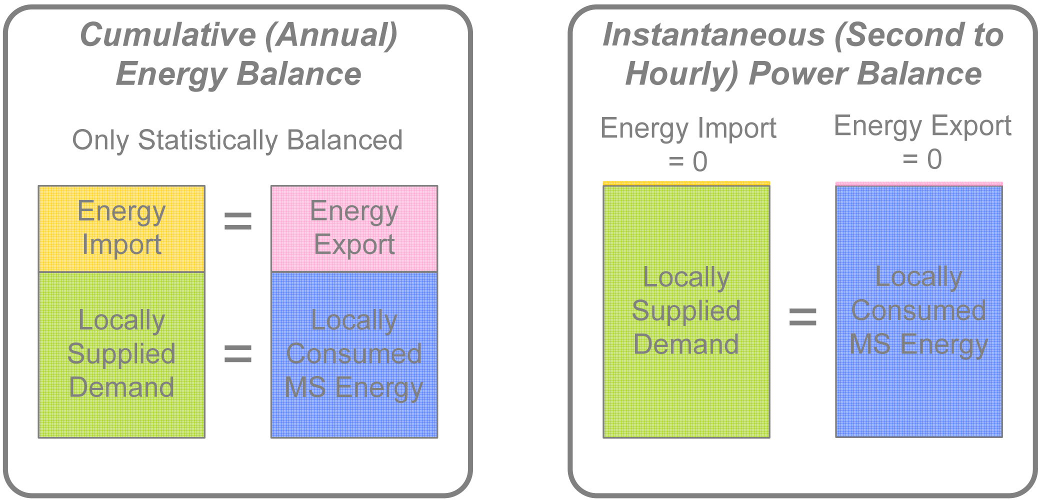


Figure 4-7 Comparison between Cumulative Balance and Instantaneous Balance

The starting point of a grid-connected Microgrid is a free exchange mode (Figure 4-8) without any restrictions: import, export, and self supply are all openly allowed and practiced.

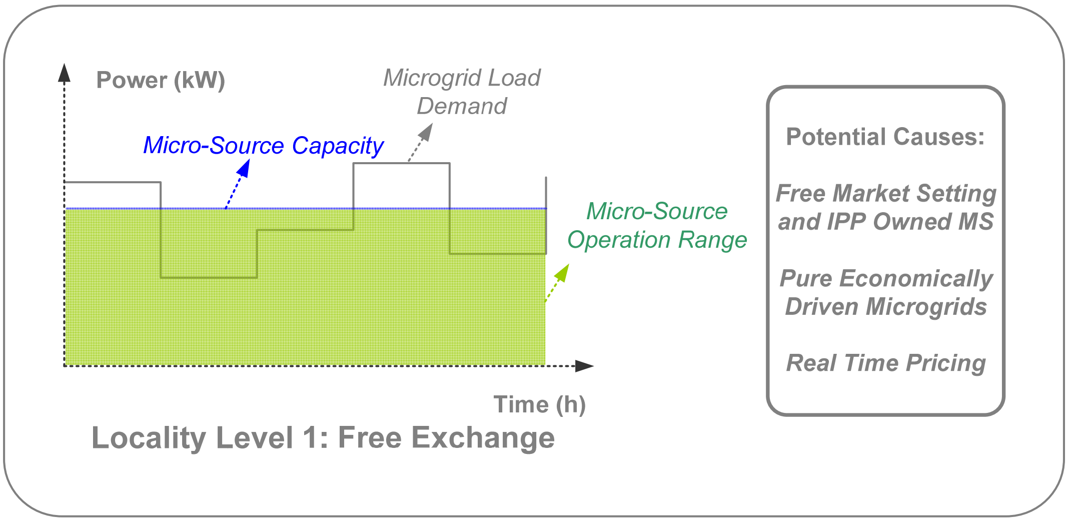


Figure 4-8 Free Exchange Level of Microgrid Locality

A short review of section 3.2.3 will reveal that locality level 1 corresponds naturally to the 'exchange' market setting with uniform and real time pricing settings.

Therefore, if external market setting deteriorates from 'exchange' scenario to 'hybrid' scenario (directional and real time pricing), the locality level of a Microgrid will be expected to increase in scale, which can lead to two potential results at locality level 2: export limitation (strict consumer) and import limitation (strict generator), as shown by Figure 4-9.

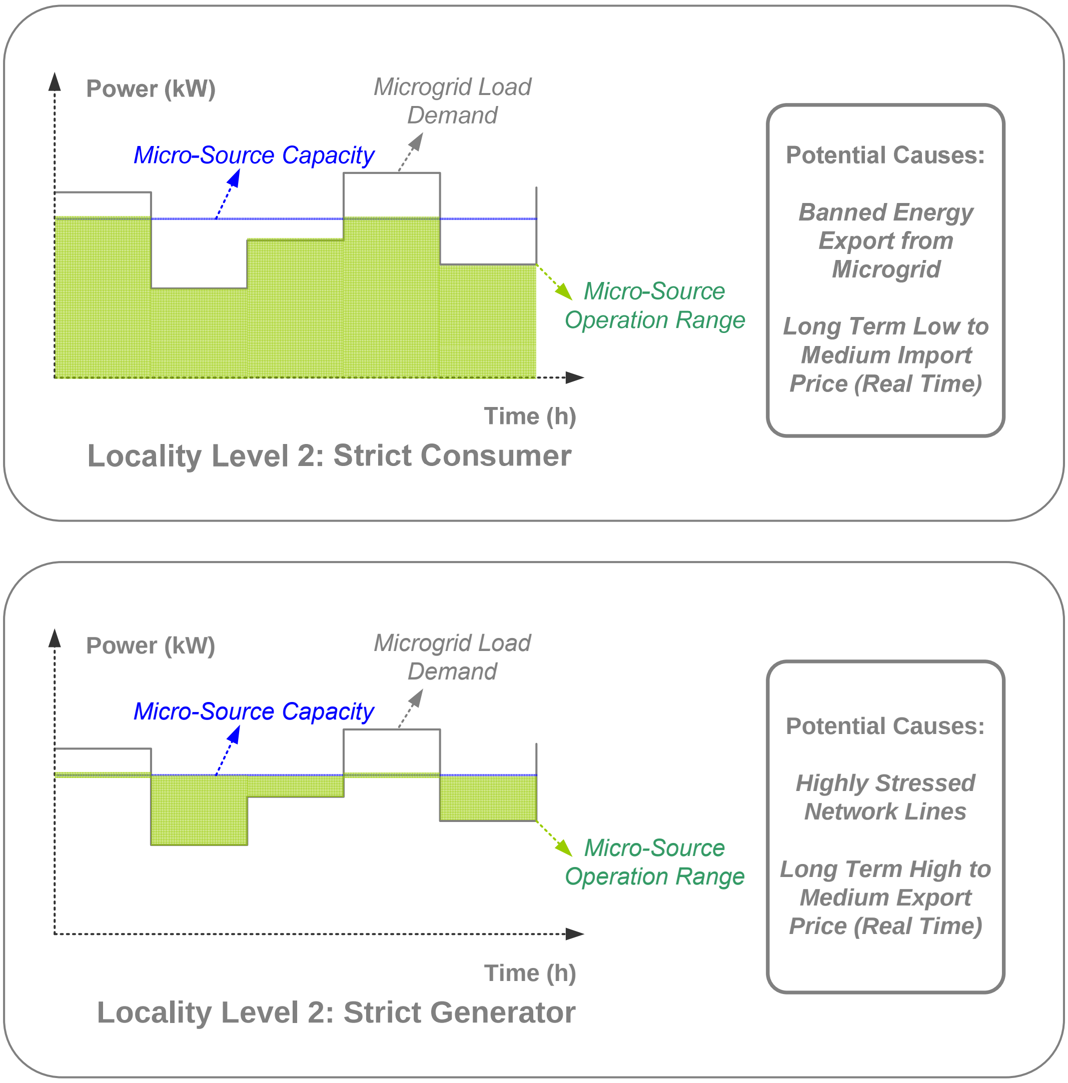


Figure 4-9 Import or Export Restriction Level of Microgrid Locality

In general, strict consumer behaviour generally happens when MS cost falls into Microgrid buying price range but stays way above selling prices, which grants local load the choice of supply sources but limits MS selling choice to local retail market. On the other hand, strict generator behaviour generally corresponds to a Microgrid with a large share of cheap MS units that feature costs in range of Microgrid selling price but stays way below Microgrid buying prices, which grants MS units with the freedom of choosing to export or not, while local consumers economically favour MS generation at all times.

Eventually, a Microgrid will enter the 'real' stage of island operation at locality level 3, as shown by Figure 4-10. Although various reasons could lead to such a result, the most likely cause in reality will be economic rather than others.

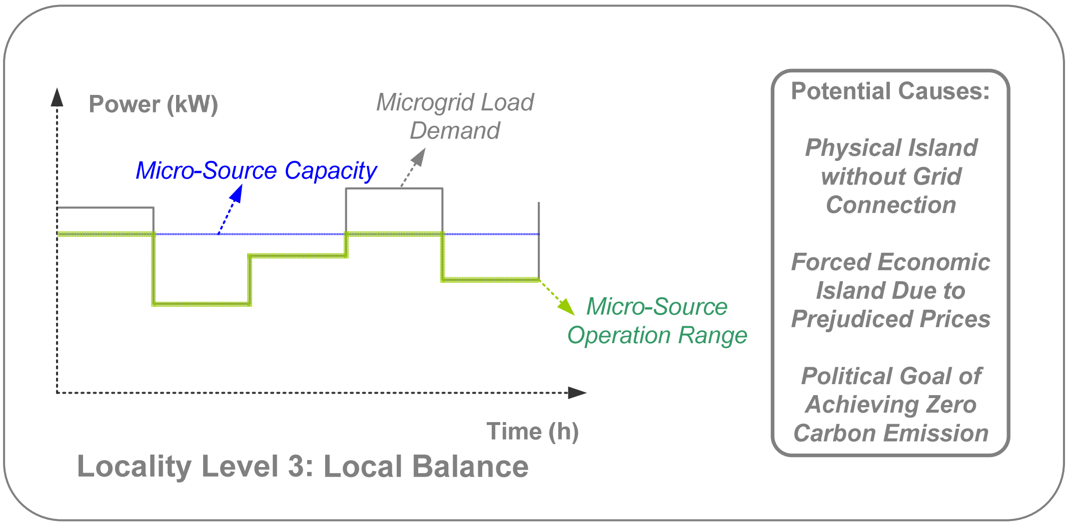


Figure 4-10 Local Balance Level of Microgrid Locality

Obviously, under emergency conditions (i.e. loss of main), a Microgrid is technically restricted to locality level 3, which is also by default the 'natural' definition of islanded Microgrid operation. In comparison with 'selective' (i.e. main grid still available) locality level 3 islanding cases caused by economic or emission concerns, this technical 'compulsory' islanding condition poses much higher requirements on the transient stability, fault ride-through as well as black-start capabilities of a Microgrid and is generally more expensive to implement in reality.

5 Setup of the European Microgrid Study Framework

One of the most challenging issues of quantifying Microgrid benefit is the definition of an evaluation framework that could accommodate the majority of input and output parameters at a manageable level of data complexity. As the constitution and performance of a Microgrid are generally subjected to a huge variety of internal and external factors, the potential scenarios to be explored within this framework can become literally numerous as a result. Therefore, in scope of this project, a European-level Microgrid study framework has been realized on three simplified layers of settings that are detailed respectively in ensuing sections 5.1, 5.2, and 5.3:

1. Location Setting, which determines network data, RES productivity, and electricity price;
2. Time Setting, which determines MS penetration scenario and cost development in Microgrid;
3. Sensitivity Setting, which covers individual market, regulatory, and operational impact factors.

This framework implies that each specific combination of location and time settings would lead to an arbitrary Microgrid setup, while the real time operation and performance of this Microgrid will be further influenced by the listed sensitivity entries.

Finally, in section 5.4 a list of representative Microgrid benefit indices are defined for respective economic, technical, and environmental aspects. They serve as quantified indication of Microgrid performance under different configurations and environments.

5.1 Location Setting: Tested EU Countries and General National Data

In this section, factual or representative economic, technical, and environmental data used for Microgrid evaluation framework are shown on a country-to-country and region-to-region basis.

5.1.1 Portfolios of Electricity Generation and Emission / Price Levels

Energy portfolios of 9 representative European countries [38] are listed in Figure 5-1; for Germany (DE), Denmark (DK), Greece (GR), Italy (IT), Macedonia (MA), the Netherlands (NL), Poland (PL), Portugal (PT), and United Kingdom (UK). It can be seen that fossil fuels (coal, oil and natural gas) remain as dominating source of energy for most countries, while RES ratios are generally low except for hydro plants in a number of countries.

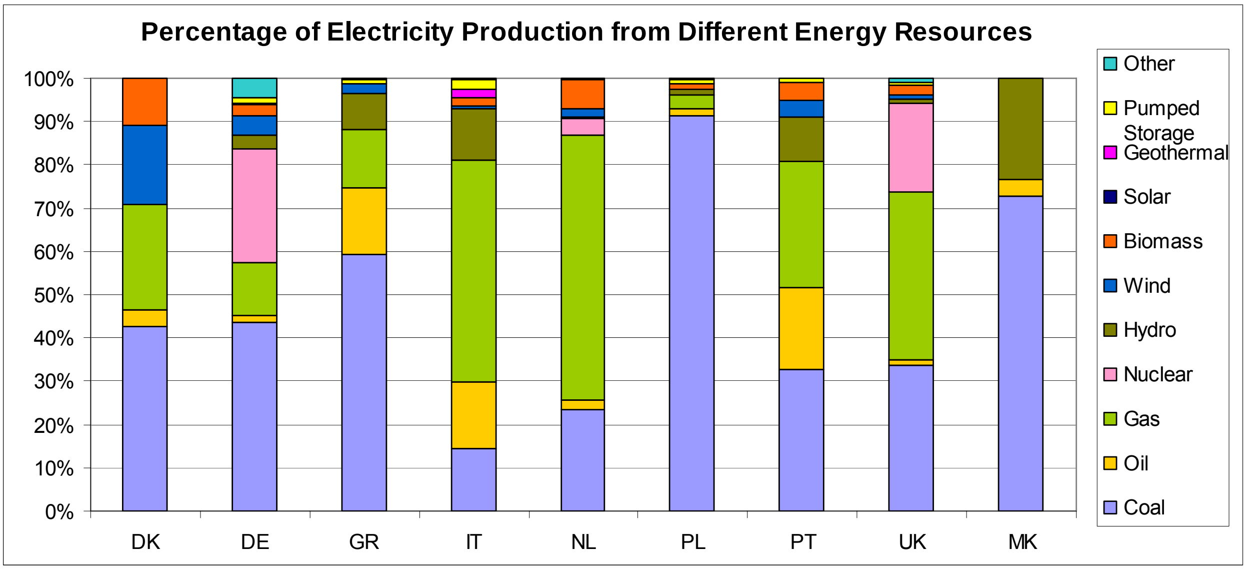


Figure 5-1 Concurrent Energy Portfolios for Electricity Generation

A short summary of emission data for both fossil and renewable resources is shown by Table 5-1. The general emission-cutting advantages of renewable resources over fossil fuels can be evidenced (may except for NOx emission from bio-fuels).

kg / MWh	Kg Emission per MWh Generated Electricity								
	CO_2_eq			SO_2			NO_x		
	Min	Max	Taken	Min	Max	Taken	Min	Max	Taken
Coal	740	960	900	0.5	12	6	0.5	4.5	3
Oil	550	850	600	1	14	5	1	12	2
Natural Gas	400	500	450	0.001	0.003	0.003	0.5	0.8	0.6
Nuclear	10	45	40	0.01	0.03	0.03	0.01	0.03	0.03
Biomass / Biogas	20	80	60	0.1	0.2	0.12	1	2	1.8
Wind Turbine	10	30	20	0.01	0.05	0.05	0.01	0.04	0.04
Photovoltaic	30	100	50	0.1	0.25	0.25	0.1	0.22	0.22
Hydro	5	30	20	N/A	N/A	0	N/A	N/A	0
Geothermal	23	41	30	N/A	N/A	0	N/A	N/A	0

Table 5-1 Emission Data of Different Energy Resources

Figure 5-2 shows that installed generation capacity and annual energy consumption figures vary significantly from country to country, which provides a considerably wide range of test subjects for disclosing Microgrid behaviour under different environments.

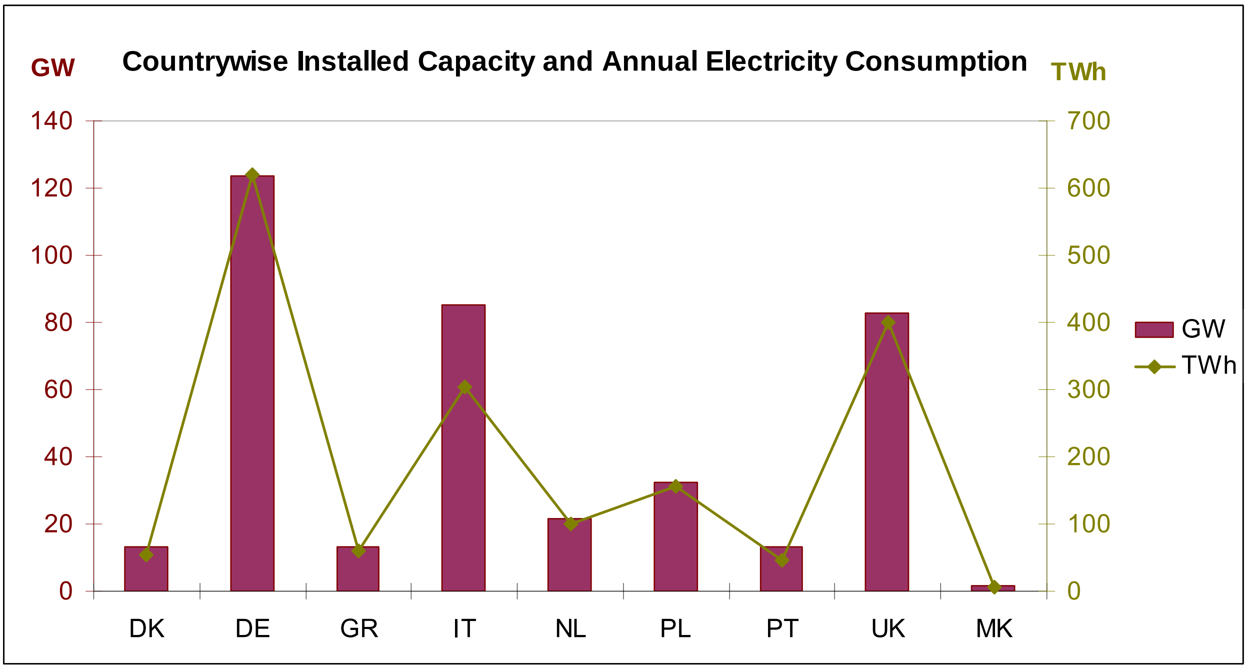


Figure 5-2 Installed Capacity and Energy Consumption per Country

A statistical summary in Figure 5-3 shows that current average wholesale price in studied countries ranges from 40 Euro/MWh to 90 Euro/MWh, while per-MWh CO_2 emission falls into the range between 400 kg and 800 kg.

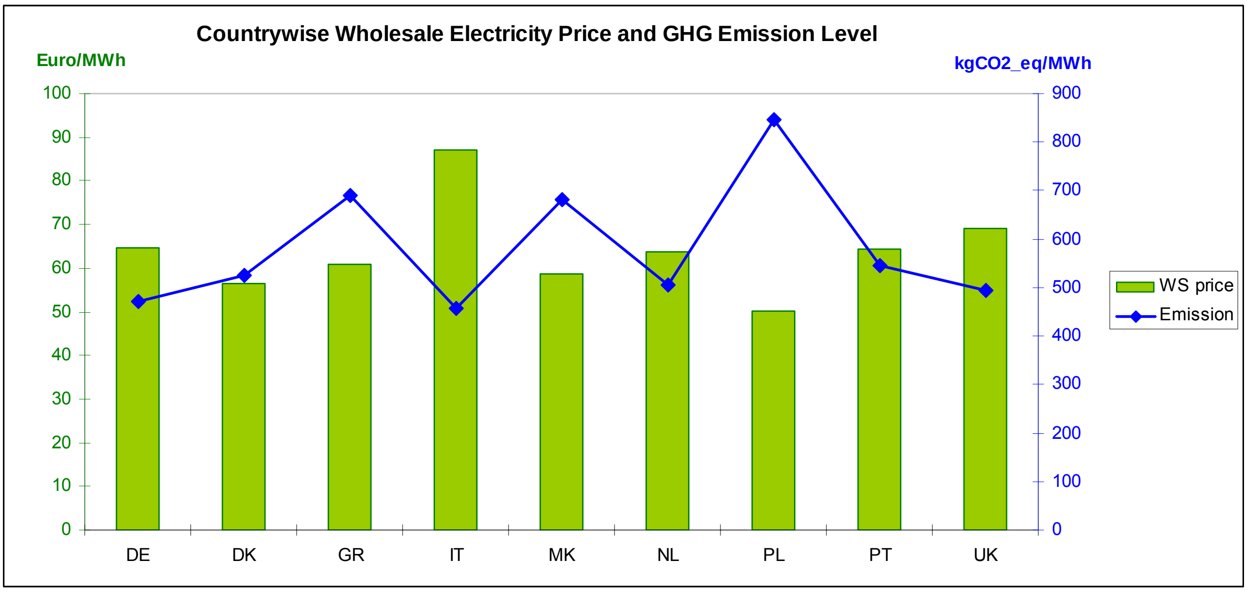


Figure 5-3 Wholesale Electricity Prices and GHG Emissions per Country

In Figure 5-4, further information is given in terms of end user retail electricity price, for which raw data are collected from Eurostat data till 2009 [39]. It can be seen that extremely large national differences in terms of tax level can be observed—ranging from high tax countries such as Denmark and Germany to low tax counterparts such as Greece, Macedonia, and UK.

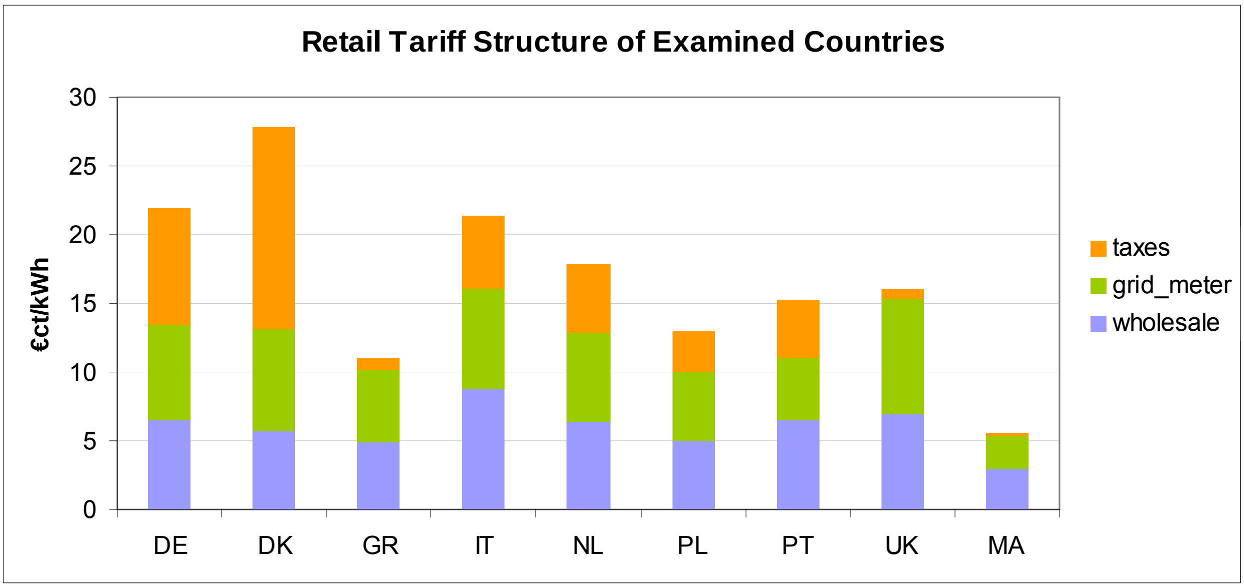


Figure 5-4 Retail Tariff Structure of Examined Countries

In Figure 5-5, the tariff structure data from Figure 5-4 is further illustrated in relative terms. Here cross-country comparisons are much easier to perform, resulting in low-tax (MA, UK, GR) level of 5% to 10%, mid-tax level of 20% to 30% (IT, NL, PL, PT), and high-tax level of 40% to 50% (DE, DK). Obviously, Microgrid support programs are generally easier to implement in high- to mid-tax countries as direct regulatory tax reduction might already provide sufficient revenues for a Microgrid to achieve profitability.

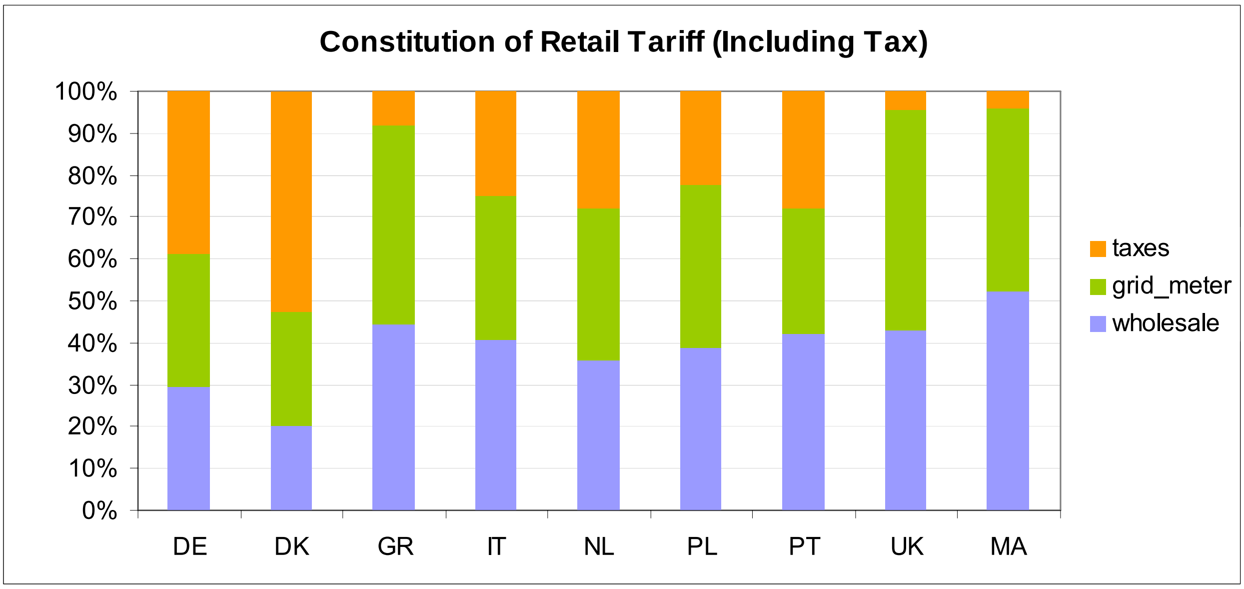


Figure 5-5 Constitution of Retail Tariff (Including Tax)

In Figure 5-6, the energy part and grid (plus metering and other services) part of retail cost are shown in relative percentages without tax intervention. Examination of ratio between these two reveals that grid charges in general account for 40% to 60% of total retail tariff (without tax) for basically all European countries under study. The directly implication from this discovery is that MS units could potentially double their revenues if they could sell at retail price level.

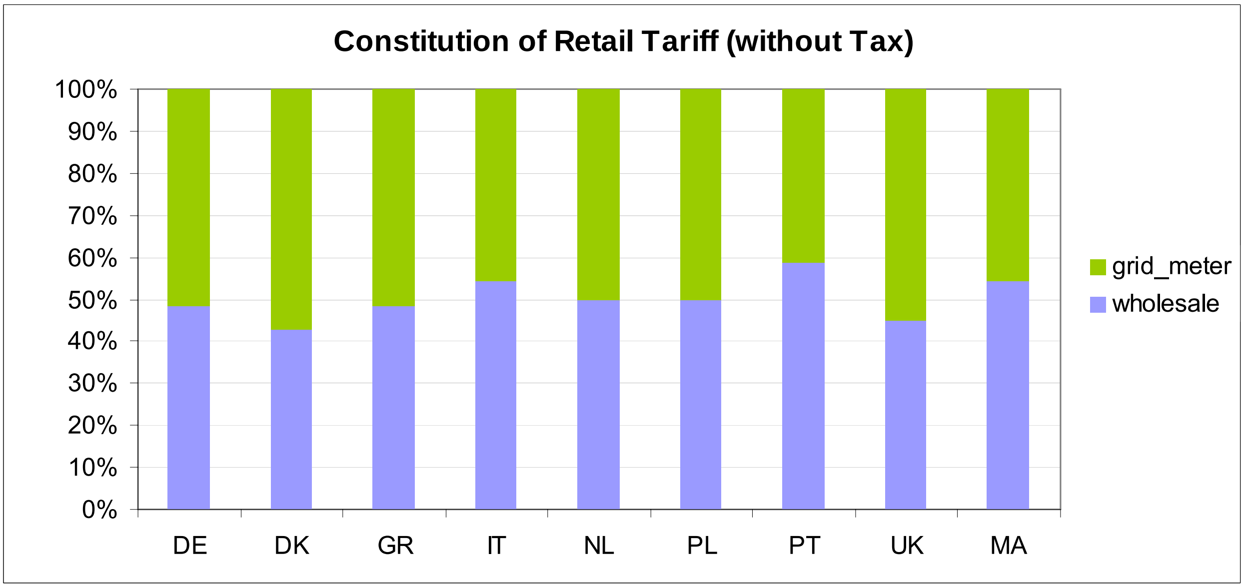


Figure 5-6 Constitution of Retail Tariff (without Tax)

5.1.2 Stochastic Modelling of RES and CHP Output

Modelling and simulation techniques for intermittent RES and heat-driven CHP units are detailed in Annex 1. In Figure 5-7, potential full load hours of PV and WT units are listed with national differences, from which a maximum of 50 % performance variation can be observed.

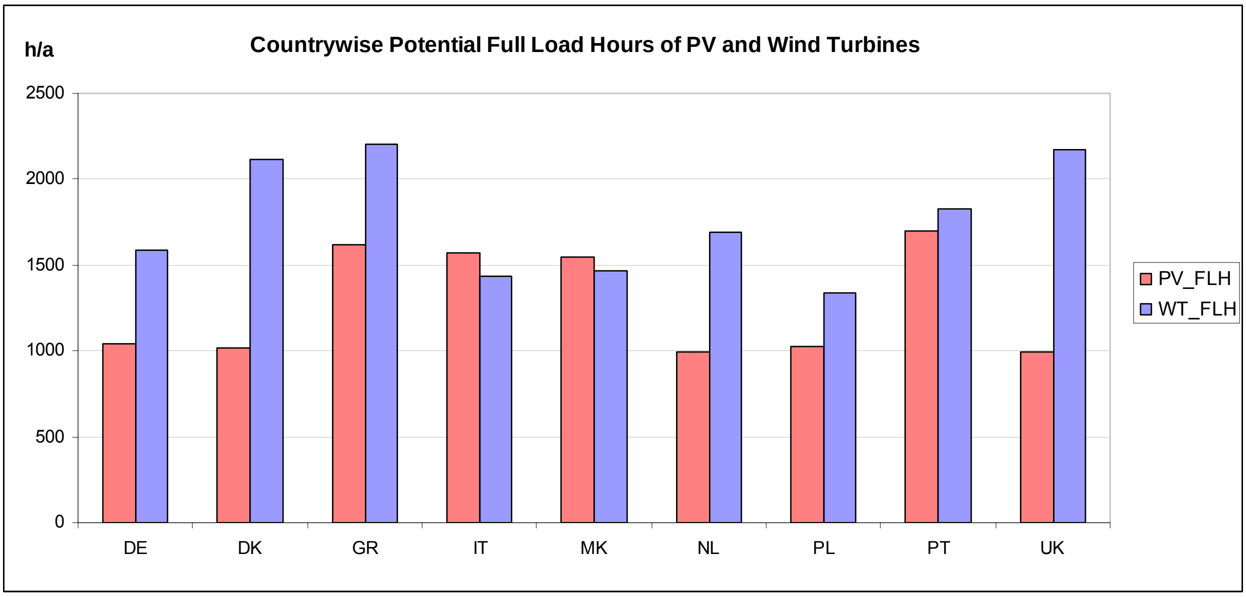


Figure 5-7 Annual Average Full Load Hours of PV and Wind Turbines per Country

Due to weaker dependency on geography, small hydro plants (SHP) and heat-driven CHP units are not differentiated from country to country. However, different CHP generation profiles are defined by different use types, as shown by the generation factors (percentage of full load hours per year) in Figure 5-8.

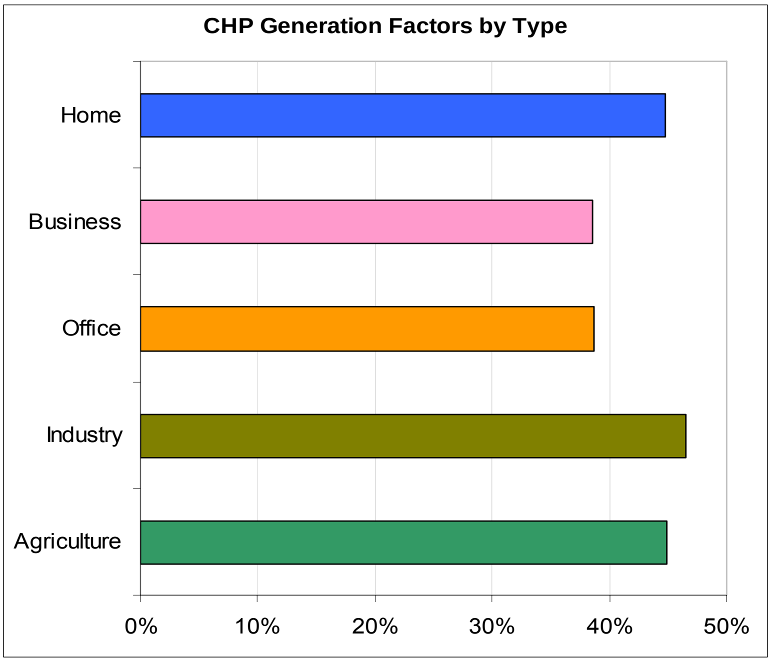


Figure 5-8 Heat-Driven CHP Generation Factors per Type

5.1.3 Case Study Network Data

Detailed topologies and grid data are listed in deliverable DG1 [8], while technical Annex 3 of this report provides more detailed views of MS allocation results.

In Figure 5-9, a summary of load factors are given for examined test grids. In general, average load factor ranges from 0.45 to 0.6 depending on country and load type. As a consequence, the listed loading levels can be theoretically satisfied with 50% to 60% of MS penetration level if all installed units are dispatchable and a sufficiently large storage unit is available.

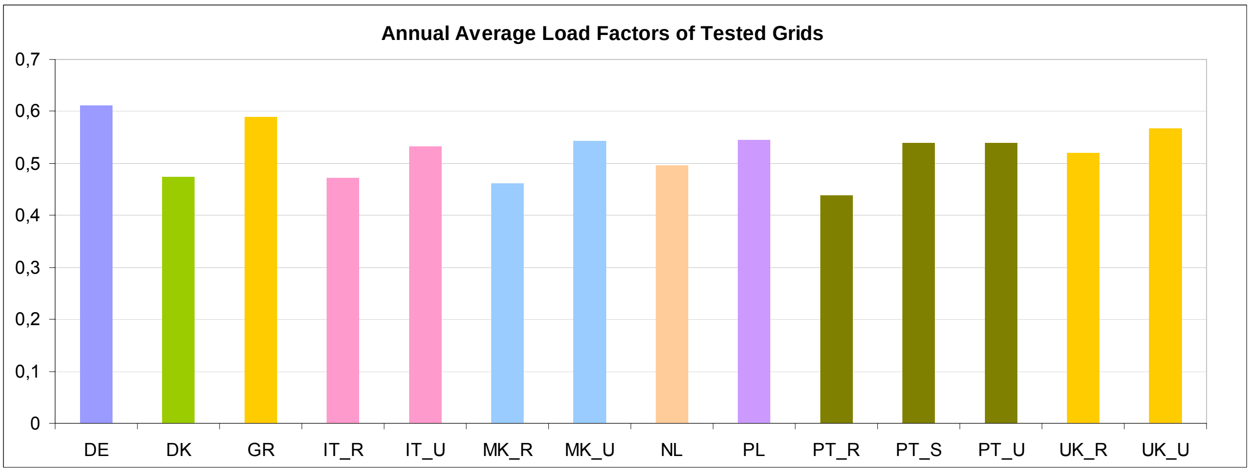


Figure 5-9 Annual average Load Factors per Country

In Figure 5-10, the relative power loss levels are listed in terms of annual average divided by total energy demand. It can be seen that per kWh losses from rural grids are generally expected to be double of urban grids in the same country, which means most rural grids have 6% to 8% of loss ratio, while most urban grids have 3% to 4% of loss ratio. Such a difference can be mainly explained by average line length and unit load sizes.

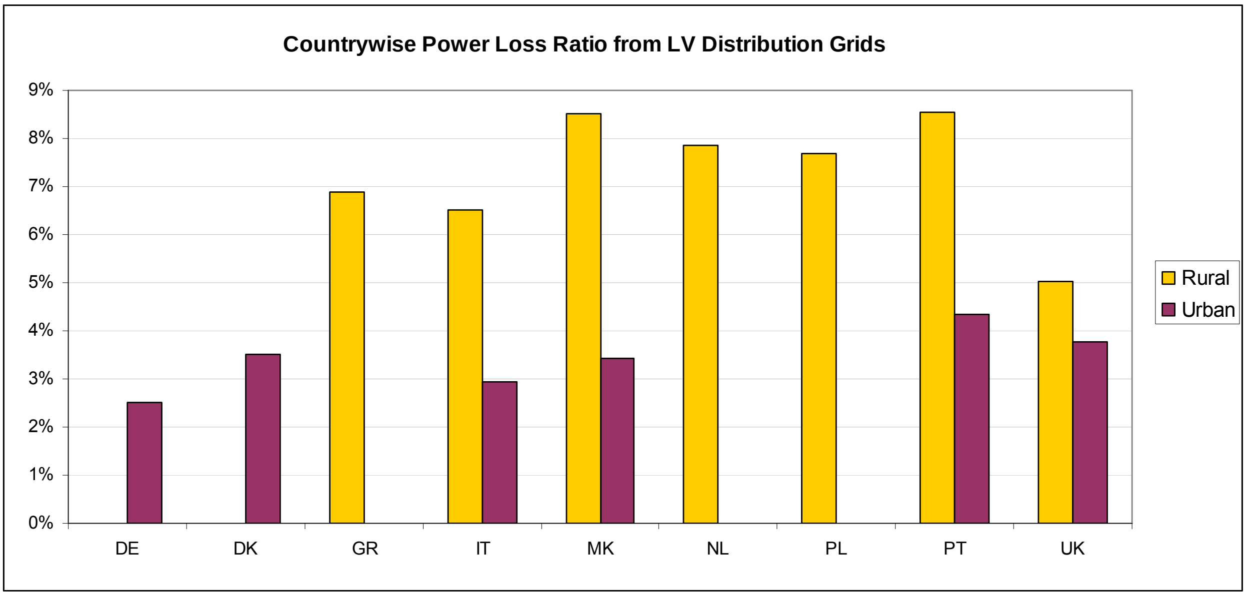


Figure 5-10 Power Loss Ratios from LV Distribution Grids per Country

5.2 Time Setting: Microgrid Penetration Scenarios and Cost Development

5.2.1 A Roadmap Layout for European Microgrid from 2010 to 2040

In section 5.1, the location settings are taken primarily as status quo or typical data that originate from either partner's contribution in deliverable DG1 [8] or Eurostat statistics [40]. However, the setup of a Microgrid is further dependent on a considerable amount of uncertainties stemming from MS unit configurations—namely, this means assumptions will be needed in terms of MS technology choice, penetration level, as well as allocation strategy on a grid-to-grid basis.

In order to minimize the potential number of simulation cases, MS allocation is assumed to be optimal for all study networks, which means a (feeder-wise) tail-to-head penetration order with type-specific MS unit dimensioning strategy has been adopted using the optimization techniques proposed in EU-DEEP project [9][12].

In scope of adopted evaluation framework, four Microgrid scenarios are respectively defined as 2010, 2020, 2030, and 2040 cases. In order to maintain a sufficient level of carbon reduction credit, it is assumed that the typical Microgrids will respectively satisfy 10 %, 20 %, 30 %, and 40 % of their own demands by RES and bio-fuelled heat-driven CHP units, which can be seen from Figure 5-11.

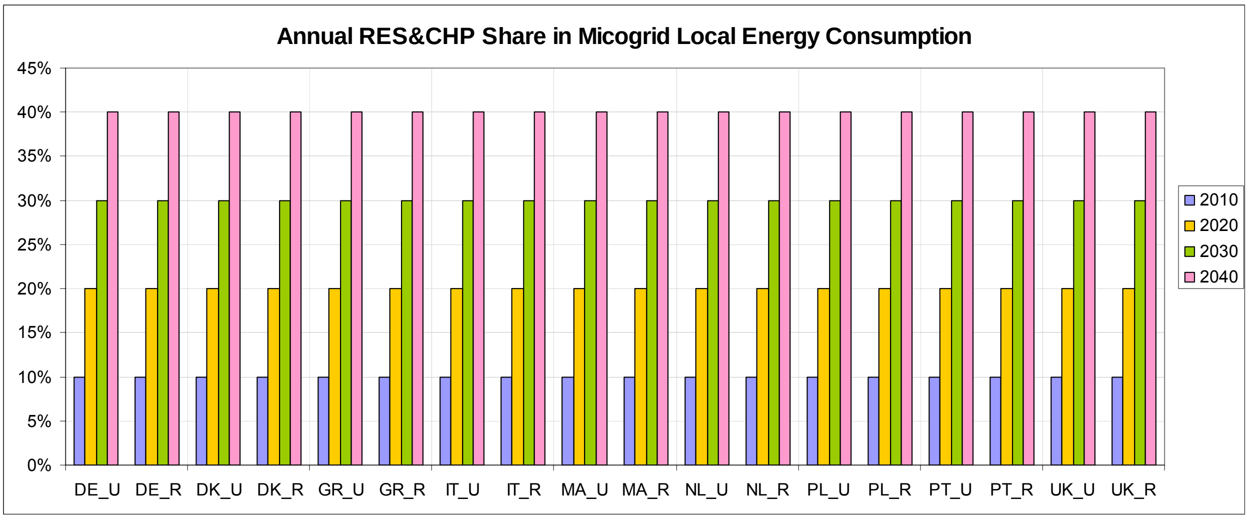


Figure 5-11 Annual RES & CHP Share in Microgrid Energy Consumption per Country

The 10% to 40% self supply levels via RES and heat-driven CHP units are of course exemplary figures used for facilitating cross-grid comparison as well as revealing the gradual increase of MS share in distribution grids over time. While there may be specific situations leading to high RES & CHP shares in 2010 or low RES & CHP shares in 2040, this proposed linear trend should find good applicability to the majority of future Microgrid implementations.

The reason for not extending RES & CHP self supply level to 50% or even higher is mainly due to MS technology configurations of some examined countries where Microgrids are expected to be dominated by RES units with low full load hours (< 2000 h/a)—in this case, more than 150% RES penetration levels might be required to meet up with the targeted self supply level, which is very likely to cause network problems in weak grids.

As active power outputs from intermittent RES and heat-driven CHP units are not dispatchable in nature, controllability of a Microgrid has to be obtained via installation of dispatchable micro-sources or storage devices. Dispatchable MS units are also the only means of increasing Microgrid self supply level (storage devices do not generate energy on their own) after RES and heat-driven CHP shares have reached saturation in a grid. In the adopted evaluation framework, penetration levels (defined by installed power capacity) of dispatchable MS units (assumed to be fuelled by natural gas) are assumed to reach 10%, 20%, 30%, and 40% in a Microgrid by year 2010, 2020, 2030, and 2040. In this way, the majority of examined Microgrids will be capable of achieving 80% to 100% total self supply level by 2040 under ideal market settings (i.e. all dispatchable micro-sources operate at maximum output levels at all times).

The choice of MS technology types for Microgrids of different countries and regions has been made according to forecast figures collected from utility partners within this project. Based on this collected data, the share of typical Microgrid in national grid can be defined as dissemination ratio, which is drawn in Figure 5-12 per country and region for 2010, 2020, 2030 and 2040 cases with both pessimistic (P) and optimistic (O) assumptions.

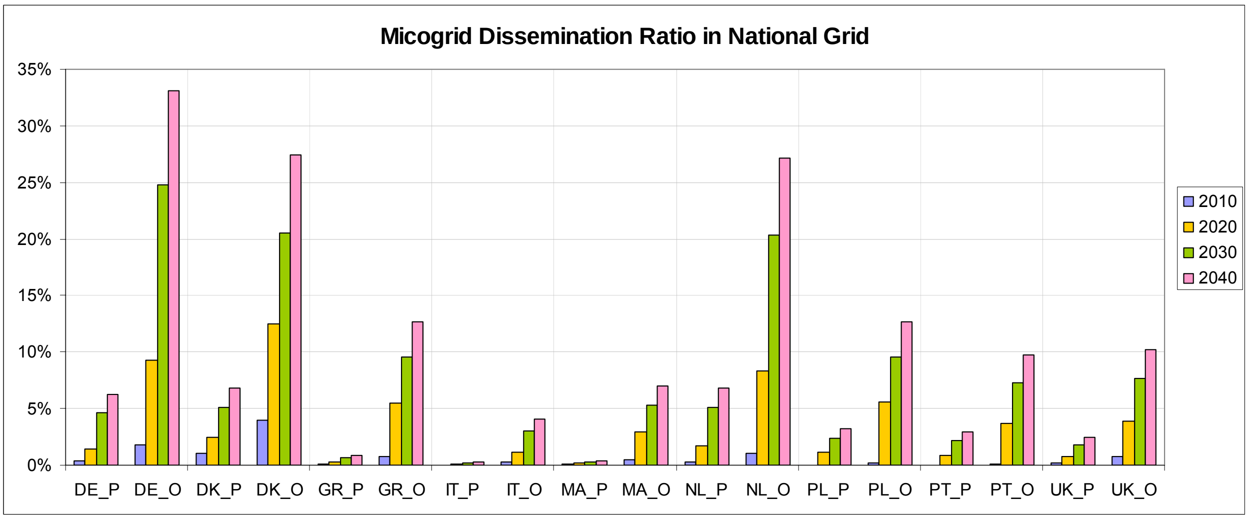


Figure 5-12 Microgrid Dissemination Ratio in National Grids

Detailed penetration scenarios of RES and CHP units in each simulated case are given in Figure 5-13. It can be seen that countries that rely heavily on PV (IT, PT) or WT (PL) units for RES energy are likely to have Microgrid configurations with >100% penetration level in 2040 simply from the renewable units.

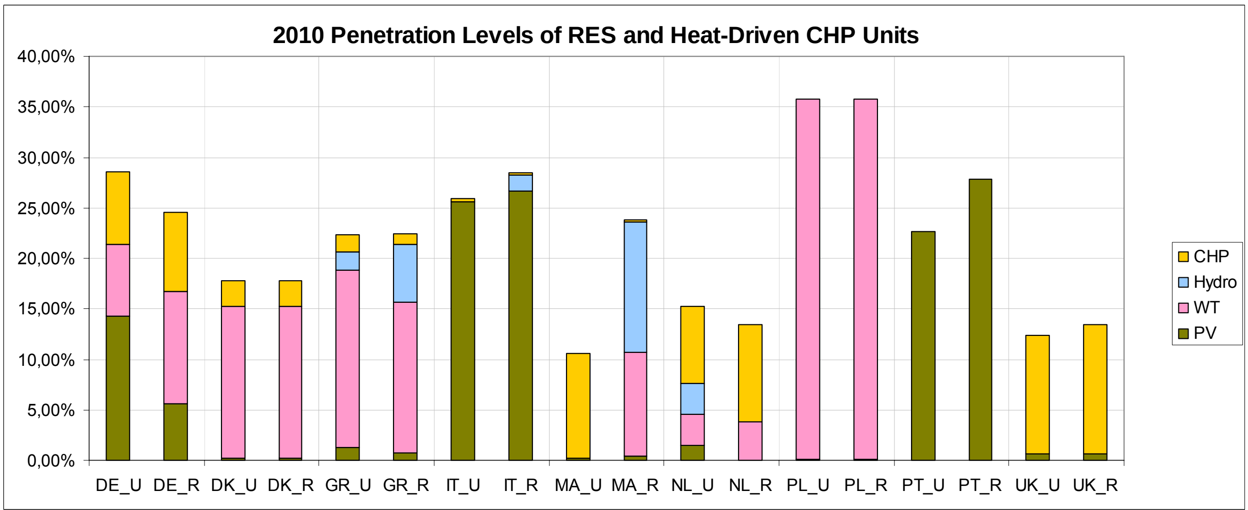


Figure 5-13 Typical Microgrid Configuration, per Country

5.2.2 Basic Assumptions of Demand and Cost Development Over Time

According to data collection result in DG1 [8], the expected annual increase rate in load level for different countries is summarised in Table 5-2.

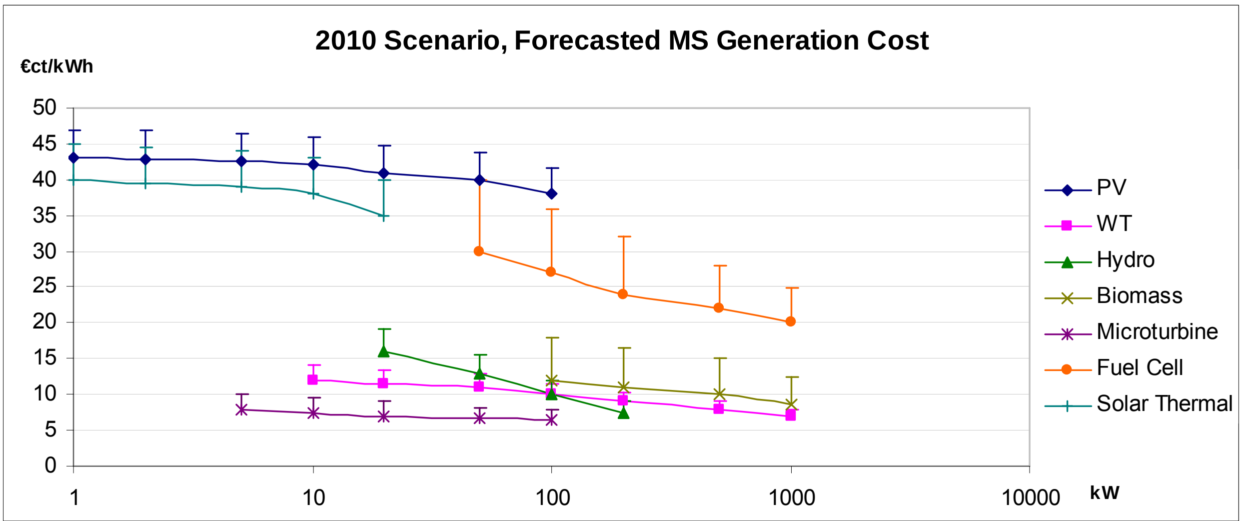
%/a	PT	PL	IT	NL	DE	GR	DK	MC	UK
2008 – 2010	3	2	2	2	0.5	3.8	0.5	3	1.1
2010 - 2020	2.5	2	2	2	0.5	2.6	0.5	3	1.1
2020 - 2030	2.5	1.5	2	2	0.5	2.5	0.5	3	1.1
2030 - 2040	2.5	1.5	2	2	0.5	2.5	0.5	3	1.1

Table 5-2 Expected Load Growth Rate from 2008 to 2040

For consistency of NPV (net present value) and annuity analysis, interest rate (depreciation rate) of all examined countries is assumed to be constant at 5% throughout the examined period. In the mean time, time-dependent development assumptions are not made for electricity market prices in examined countries and regions due to observation of both increasing and decreasing trends in the past two decades according to Eurostat data [40].

In Figure 5-14, graphical representations of per-kWh MS generation costs is given for different technology options under 2010, 2020, 2030, and 2040 settings. Errors bars in the plots correspond to cost variations of a MS unit with a specific size due to different output levels (further details given in ensuing section 5.2.3).

According to Figure 5-14, drastic cost reductions are expected from PV and fuel cell technologies between 2010 and 2040; while other RES options are assumed to advance in milder steps. Natural gas based Micro Sources (mainly Micro-turbines) are expected to face increasing fuel cost due to deteriorating resource scarcity.



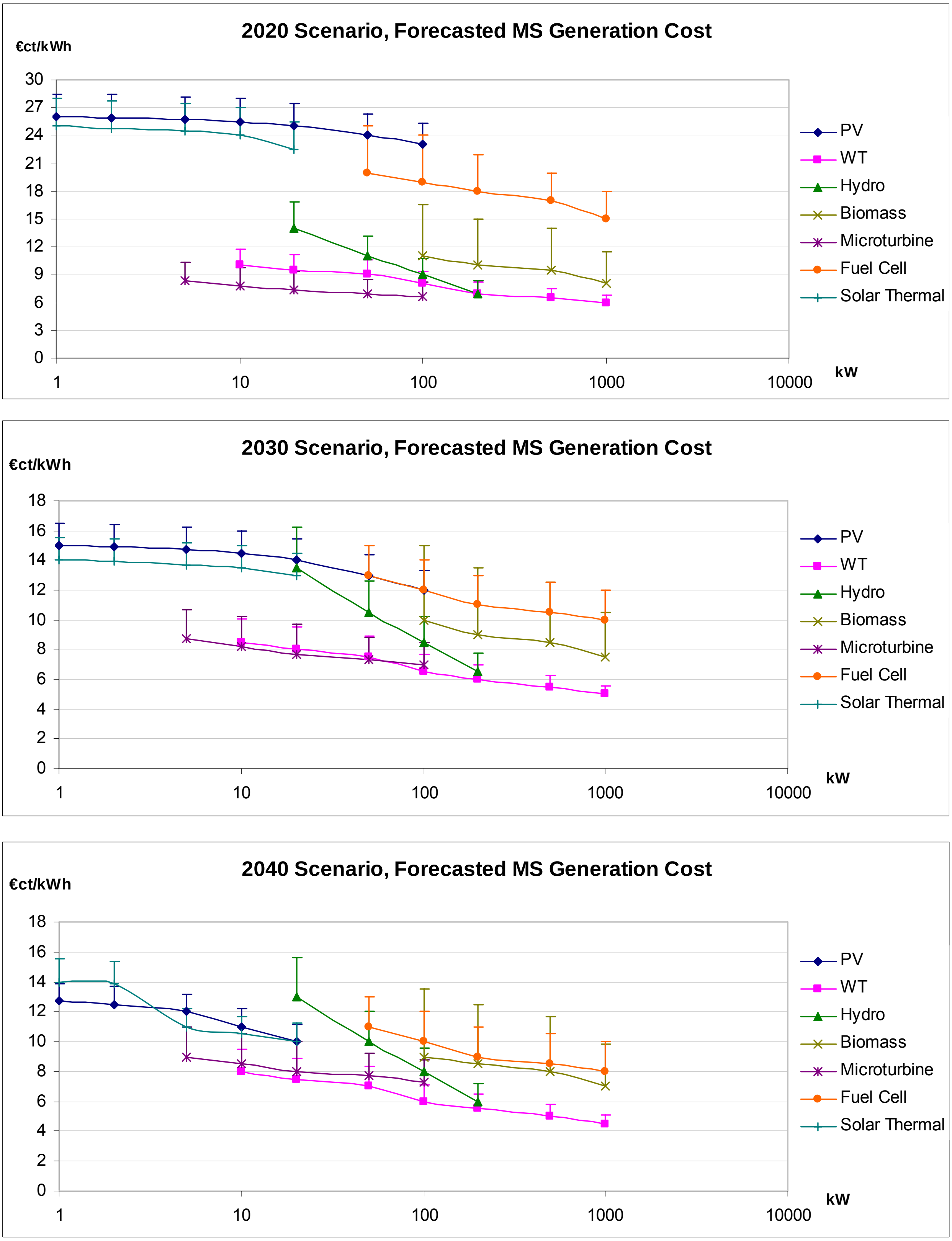


Figure 5-14 Pan European Micro Source Generation Costs

5.2.3 Cost Model Explanation for Dispatchable Micro Sources

Since dispatchable MS units are considered as the main source of controllability within a Microgrid, real time system optimization decisions will be strongly dependent on its cost modelling. In addition to rating related features shown by Figure 5-14 (i.e. mainly gas fired Micro-turbines with typical cost range of 70 to 90 €/MWh), a quadratic generation cost model dependent on dispatchable MS unit output level is assumed in equation (5-1):

$$Assume: \quad P \text{ as active power output of dispatchable MS unit, } k \text{ as per kWh generation cost,}$$

$$Then: \quad k = a + b \cdot P + c \cdot P^2$$

with (5-1)

a as constant order coefficient, includes power related investment and installation costs

b as 1st order coefficient, includes energy related fuel, O & M, and emission costs

c as 2nd order coefficient, refers specifically to unit efficiency related costs

The constant and first order coefficients (generally referred to as power-related and energy-related constants) generally hold deciding impacts over dispatchable MS unit generation cost. Under the framework of future Microgrid evaluation, cost modelling of dispatchable MS units should cover the following aspects: investment and installation costs (constant order), fuel and emission costs (first order), as well as control, metering, and communication costs (constant and first orders).

Investment and Installation Cost Consideration

Investment and installation costs are also referred to as 'sunk cost' in the sense that they are not dependent on real-time dispatch decisions. Nonetheless, translation of these costs into a zero order coefficient in equation (5-1) requires two assumptions: (1) device life time used for annuity method, and (2) an estimation of unit full load hours. Both terms are explained in equation (5-2).

$$\begin{aligned}
Assume: \quad & B \text{ as inital capital value,} \quad A \text{ as equivalent annual cash flow,} \\
& FLH \text{ as estimated full load hours of DMS unit,} \\
& k_{inv\&ins} \text{ as per kW investment and installation cost} \qquad (5\text{-}2) \\
Then: \quad & A = \frac{B}{\beta} = B \cdot \alpha \quad (\alpha = \frac{1}{\beta} \text{ as annuity factor}) \\
& k_{inv\&ins} = \frac{A}{FLH} = \frac{B}{\beta \cdot FLH}, \quad \beta = 12.5 \text{ for } 20 \text{ years lifetime}
\end{aligned}$$

Annuity method (which distributes initial capital value evenly into all operating years) is further illustrated by Figure 5-15:

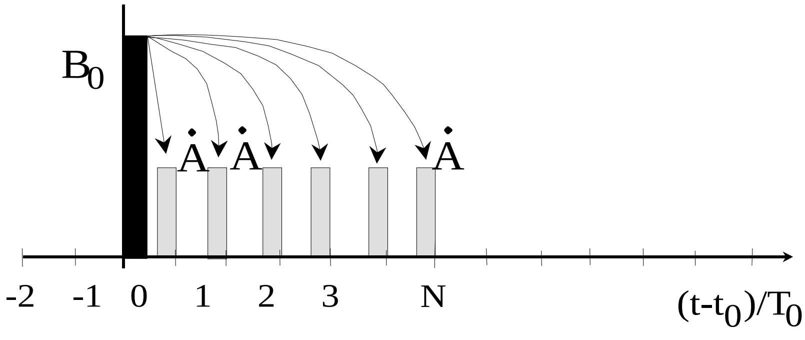


Figure 5-15 Annuity Method (Source [41])

Fuel and Emission Cost Consideration

As most dispatchable MS units are assumed as gas-fired, the first order cost entry in (5-1) will be strongly dependent on natural gas price fluctuations. However, considering the fact that spot price in electricity market is also closely correlated to natural gas price developments, it is easier to assume a constant natural gas price both inside and outside of Microgrids for convenience.

In Figure 5-16, the development of EU ETS emission trading price is given as historical data. Despite strong fluctuations in the first launch period, emission cost stabilizes since 2009 to 12-15 €/ton CO2. Thus using the 0.45 ton/MWh emission data for natural gas-fired units, emission cost in range of 6 €/MWh (+/- 20%) is assumed and considered as a part of 1st order coefficient for all MS units. Thus emission cost is included as a part of real time dispatch data.

Figure 5-16 EU ETS Trading Price for CO_2 Emission (Source: EEX [42])

- **Control, Metering, and Communication Cost Consideration**

In order to realise real-time Microgrid control, corresponding investment and service costs will occur as a consequence of intelligent network conversion. This additional cost entry is mainly dependent on the complexity of Microgrid (the number of nodes to be monitored and controlled). In order to translate this cost to per MWh value, nodal power rating is needed as Figure 5-17.

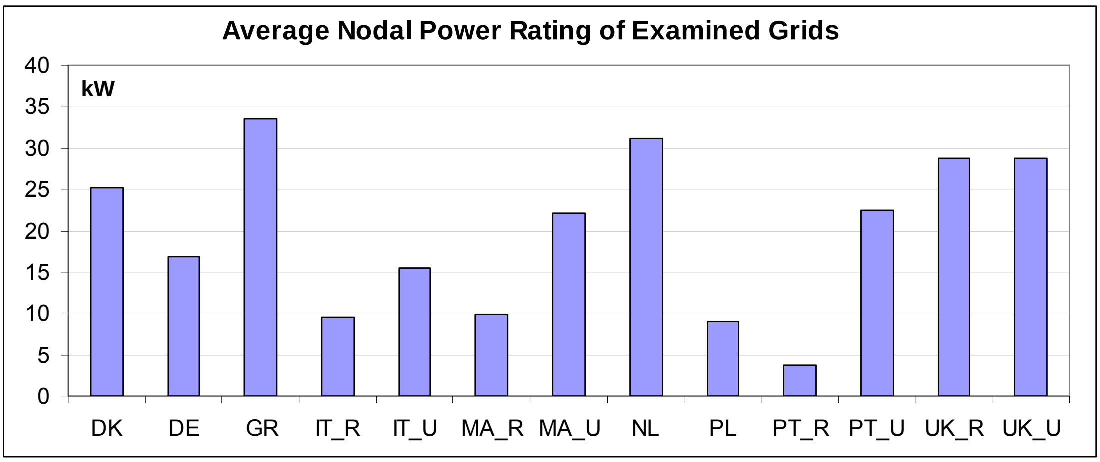


Figure 5-17 Average Nodal Load Power Rating of Examined Test Microgrids

In Figure 5-17, the majority of mean nodal power ratings are in the range of 10 - 32 kW, thus assuming 5000 h/a as general demand FLH, then annual nodal energy demand should be 50-160 MWh/a for most tested Microgrids. Ensuing cost calculations are:

$$\begin{aligned}
&Define: \quad k_{act} \text{ as annual active control cost of a node}, \quad K_{ctrl} \text{ as investment cost of control device} \\
&\qquad\qquad k_{met} \text{ as annual metering fee}, \quad k_{com} \text{ as annual communication fee}, \quad \beta \text{ as NPV factor} \\
&Then: \quad k_{act} = \frac{K_{ctrl}}{\beta} + (k_{met} + k_{con}), \quad \beta \cong 12.5 \frac{1}{a} \,(20 \text{ years life time}) \\
&Assume: \text{ For } 2010, \; K_{ctrl} = 500 \text{ Euro}, \quad k_{met} = 100 \text{ Euro}/a, \quad k_{con} = 60 \text{ Euro}/a, \\
&\qquad\qquad \text{For } 2040, \; K_{ctrl} = 250 \text{ Euro}, \quad k_{met} = 50 \text{ Euro}/a, \quad k_{con} = 30 \text{ Euro}/a, \\
&Then: \quad k_{act} = \begin{cases} (500/12.5 + 100 + 60) \text{ Euro}/a = 200 \text{ Euro}/a \text{ in } 2010 \\ (250/12.5 + 50 + 30) \text{ Euro}/a = 100 \text{ Euro}/a \text{ in } 2040 \end{cases} \\
&\Rightarrow \text{Per MWh control, metering, communication cost} = \frac{[100, 200] \text{ Euro}/a}{[50, 160] \text{ MWh}/a} = [0.6, 4] \text{ Euro/MWh}
\end{aligned} \tag{5-3}$$

Equation (5-3) suggests that Microgrid benefit should exceed 0.6-4 €/MWh (load perspective) to justify active control measures. As this additional cost is not dependent on MS operation decisions, it is used as an external comparison entry after Microgrid benefit has been identified.

5.3 Sensitivity Setting: Individual Entries for Microgrid Sensitivity Analysis

5.3.1 Sensitivity Entry 1: Wholesale Market Price Level

Due to the extremely volatile nature of wholesale electricity price, it is not clear whether future electricity price will increase or decrease based on current level. Therefore, electricity prices in all countries are assumed to be decoupled from the passage of time, and three general price levels are assumed for all countries regardless of simulation time setting.

In Figure 5-18, the annual average values of high-, mid-, and low-prices at wholesale level are shown respectively as annual average values for examined countries. The high price scenarios are taken as historical peak from the past decade, while mid and low cases are respectively calculated as 80 % and 60 % of peak value.

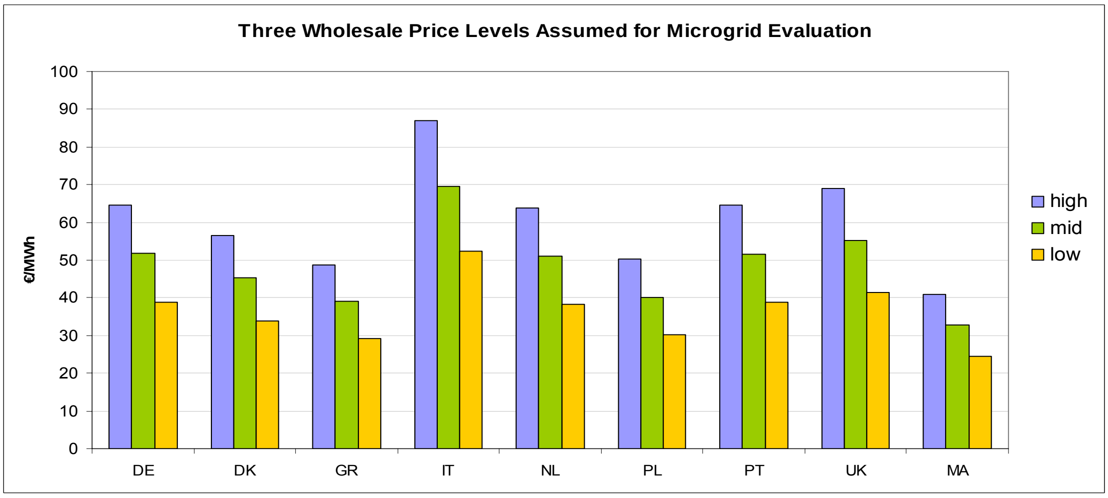


Figure 5-18 Three Wholesale Price Levels Assumed for Microgrid Evaluation

5.3.2 Sensitivity Entry 2: External Price Setting

As already discussed in section 3.2, external price setting could hold a critical impact over Microgrid profitability. In Figure 5-19, three potential price setting policies are respectively defined as sensitivity inputs for Microgrid evaluation, namely they are:

Pricing Case 1 (Constant Pricing): Directional + Constant Pricing: Economic Island

Pricing Case 2 (Flexible Pricing): Directional + Variable Pricing: Mixed Behaviours

Pricing Case 3 (Uniform Pricing): Uniform + Variable Pricing: Bidirectional Exchange

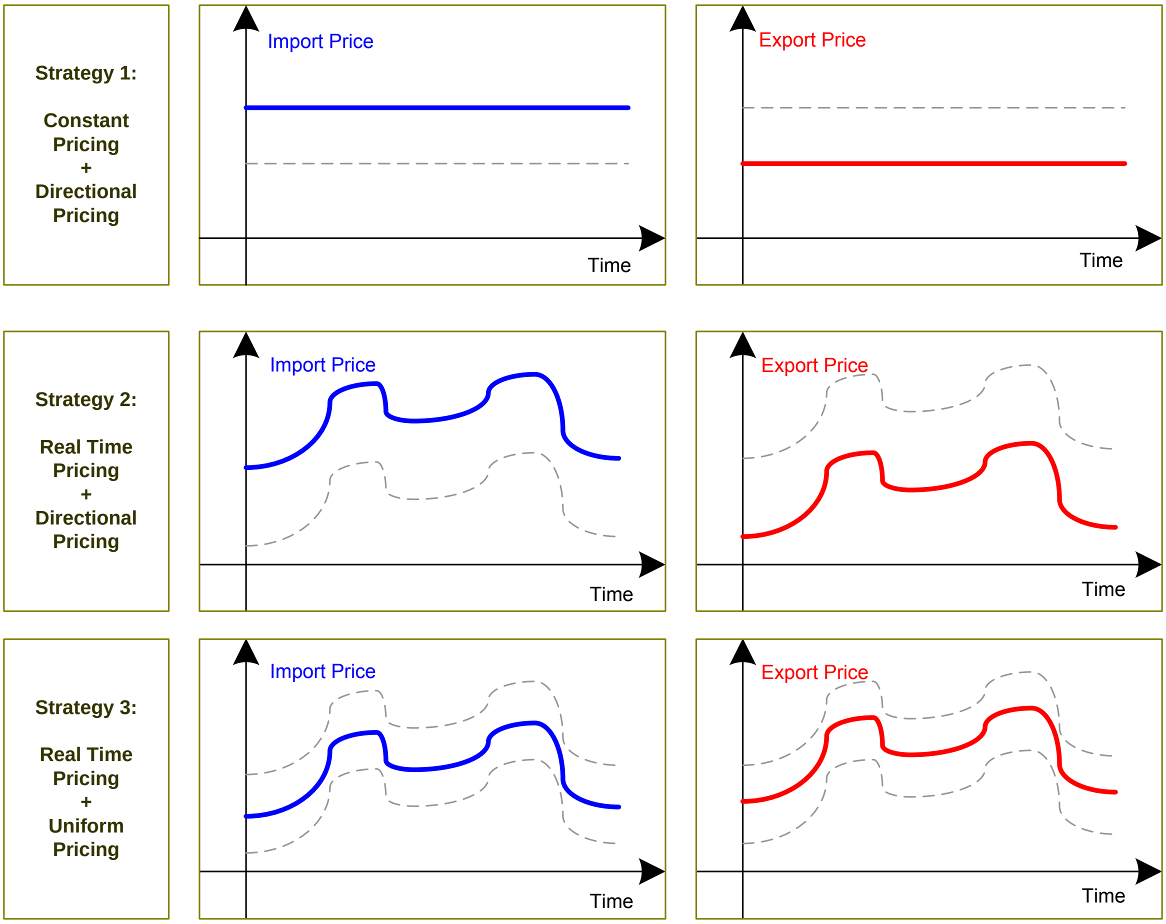


Figure 5-19 External Price Setting Policies Applied to Microgrids

In order to ensure Microgrid profitability under low market price condition, acknowledgement of local consumption is assumed for all sensitivity cases here.

5.3.3 Sensitivity Entry 3: Operation Strategy

In accordance with operation modes suggested in section 4.2.2, Microgrid scheduling has been performed under all four options:

1. Combined option (default): with summarized total cost objective and all technical constraints;
2. Economic option: with economic function as objective and no technical constraints;
3. Technical option: with loss function as objective and all technical constraints;
4. Environmental option: with emission function as objective and no technical constraints.

5.3.4 Definition of Standard Test Conditions

Due to the comparatively large amounts of simulation trials, a basic standard test condition (STC) is defined to evaluate Microgrid benefit under a ‘most likely to happen’ basis. In short, the STC conditions refer to Microgrid internal setup and operating environment combinations that are expected to occur with highest probability, which can be summarized by following features:

1. Mid-level wholesale market price level (referred to section 5.3.1)
2. Real-time and directional price setting scheme (referred to 5.3.2)
3. Combined operation mode referred to (5.3.3)

In section 7.2, all three conditions will be modified as sensitivity entries for evaluation of Microgrid performance under varied external environments.

5.4 Definition of Microgrid Benefit Indices

In Figure 5-20, a short summary of Microgrid benefits in economic, technical, and environmental aspects is given. Each benefit item is in consequence mapped to the related recipient with dotted lines. Obviously, identification of Microgrid benefits is a multi-objective and multi-party coordination task. In ensuing sections, detailed definitions are given for each of the benefit item shown by Figure 5-20.

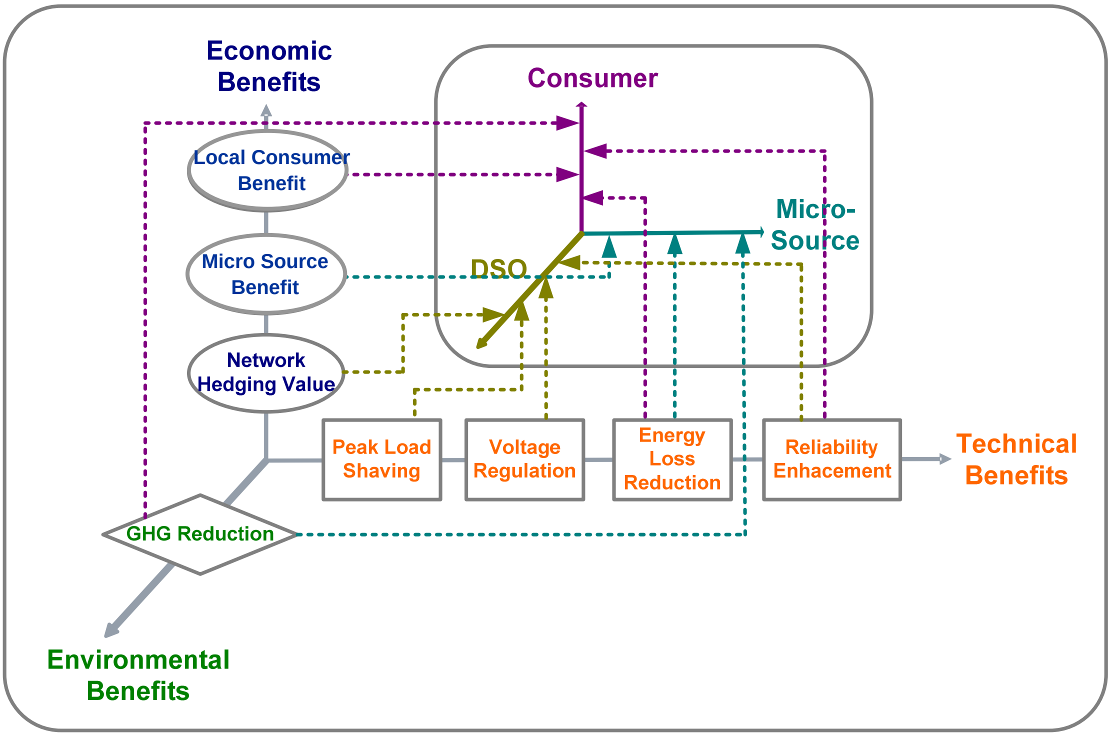


Figure 5-20 Overview of Microgrids Benefits

5.4.1 Economic Benefit Indices

As network hedging value can be seen as a direct economic consequence of peak load shaving effect from the technical part of Microgrid benefit, it is not examined in detail in ensuing simulations and is therefore skipped over in this definition section.

5.4.1.1 Local Consumer Benefit

Local Consumer Benefit (LCB) (end consumer perspective) refers to the theoretical room for retail price reduction. It is based on the assumption that all economic benefits of a Microgrid will be obtained by the end consumers, which is most likely to happen under Prosumer consortium ownership model proposed in section 3.1.2, where consumers own and operate multiple number of MS units as an aggregated Prosumer entity. The LCB can be defined either as relative value (%) or absolute value (€/kWh) as follows:

LCB (p.u.) = 1 – ideal Microgrid consumer electricity price / average price from retail market

LCB (€/kWh) = average price from retail market – ideal Microgrid consumer electricity price

There are potentially two components that could contribute to Local Consumer Benefit:

(1) Locality value of (subsidized) RES energy:

Under default 'natural market' (decoupled local demand and supply) setting, end consumers are not likely to benefit from any production from local (mostly intermittent) RES units if they do not actually own or operate them. This is mainly caused by the fact that the majority of RES technologies on micro scale are currently not commercially profitable even when sold on retail price level and thus need financial supports for actual deployment, which means the subsidized RES units will not see any revenue boost by switching to local retail market and are thus not sufficiently motivated to share their interests with local consumers.

As a consequence of weak market driver for direct trading between local load and subsidized RES units, the only way of disseminating potential values created by the synergy of local consumer and subsidized RES units to consumer side is forced regulatory intervention. In this case, end consumers can be financially awarded by consuming locally generated RES energy via grid charge reduction and/or emission tax exemption. The reasoning behind grid charge reduction is mainly the avoided usage of transmission and MV distribution grids for locally supplied energy, while emission tax exemption measures can be primarily attributed to the argument that end consumers within a Microgrid should not pay emission fees (if applicable) for consuming electricity produced from local RES units.

Despite logical applicability, the physical transfer of locational value of subsidized RES units to local consumers will undoubtedly place extra financial support requirements on top of existing ones (FIT, premium etc.) aimed for RES generators only. In the end, the reduction of electricity tariff for consumers within a Microgrid in this fashion will be achieved through the additional increment of retail prices applied to normal consumers that do not belong to any Microgrid or other self-generation schemes. Such a trade-off might be viewed as a political drawback that leads to veto of suggested consumer motivation programs under a conservative environment, while the same consequences can be also considered as a major driver for public acceptance of Microgrid concept and directly induces higher support levels for Microgrids.

(2) Selectivity value of retail competition

As all dispatchable MS units that are able to compete with traditional generators at retail price level are assumed to be capable of offering 'over-the-grid' energy delivery service to consumers within a Microgrid, end consumers are allowed with greater selectivity in terms of energy supply. This extra selectivity can be determined solely by MS costs at different loading levels when constant pricing scheme is applied, or both MS cost-loading dependency and instantaneous market price could hold direct impact over the extent of selectivity when real time pricing scheme is adopted.

Under an ideal setting with maximum market efficiency, the total selectivity benefit created by local retail market can be expressed as cumulative opportune cost reduction (plus opportune revenue of energy export, if applicable) for supplying energy demand of a Microgrid. This ideal selectivity benefit is calculated based on hour-to-hour selection of lower bidder between local MS energy and external generators. Obviously, the theoretical monetary value of selectivity benefit can be extracted on the basis of assuming zero profit for MS units (selling at bottom price) and zero benefit for end consumers (paying default retail tariff). By allocating this entire selectivity benefit to consumer side (i.e. assuming MS units are not operated for profit), the selectivity value of retail competition on consumer side can be expressed as:

Maximum Consumer Selectivity Benefit = Total Selectivity Benefit / Total Energy Consumption

5.4.1.2 Micro-Source Benefit

Micro Source Benefit MSB (MS perspective) mainly refers to the maximum potentials of selling price increment under a Microgrid setting. This benefit index is of course based on the assumption that consumers and DSO do not hold any share over the economic values of a Microgrid. This is most likely to happen under a pro-MS free-trading environment as shown in section 3.1.3. The MSB can be defined either as relative value (%) or absolute value (€/kWh) as follows:

MSB (p.u.) = 1 – average wholesale price / average price for aggregated model

MSB (€/kWh) = average price for aggregated model – average wholesale price

MSB as a whole can be seen as approximately equal to the maximum amount of avoided UoS fee by selling to local consumers in an over-the-grid fashion. In another perspective, MSB can also be simply understood as the difference between average retail and wholesale price levels. Notably, the MSB benefit is applicable as long as MS unit is actually selling to local and/or external consumers; this means any MS unit that relies entirely on local retail market for profit will receive this benefit regardless of its type (intermittent RES or dispatchable MS).

In further detail, MSB can be brought down to two components:

(1) Locality value of local retail opportunity (i.e. minimum profitability threshold)

The locality value can be understood simply as the difference between MS cost (supposed to be high) and average wholesale market price. The value of this part of MSB benefit will be positive when MS cost is higher than wholesale price level and negative when MS cost is lower than wholesale price level. Being negative in the latter case, however, does not suggest that MS units could be unprofitable in a Microgrid—on the contrary, negative locality value points to the situation that MS units can already make a profit by simply selling to wholesale market, although introduction of local retail chances could raise this profit margin even higher.

Therefore, the locality value on MS side can also be understood as the minimum level of revenue increment (on top of wholesale price) required for maintaining economic feasibility of dispatchable MS units. Under traditional grid concept, such a gap (in case the locality value is positive) can only be met by external financial support measures—however, a Microgrid makes it possible for a MS unit to obtain much higher prices compared to wholesale level and cover this required revenue increment (and possibly even more) via local retail market.

It should be noted that this locality value on MS side is solely determined by wholesale price and MS cost, thus the profitability and operation status of a MS unit can be seen as completely decoupled from this index. In this sense, locality value on MS side is not directly an outcome of Microgrid concept, but rather an economic requirement placed upon Microgrid design.

(2) Selectivity value of market mechanism

The selectivity part of MSB value can be explained as the difference between ideal selling price and basic generation cost of MS units in a Microgrid. Here the ideal selling price is determined by assuming a MS-dominated Microgrid with all benefits created by local market flowing directly to MS side. Similar to the case of determining selectivity benefit on consumer side, the applied benefit index to MS side in terms of market selectivity is a theoretical maximum that requires zero benefit transfer to consumer (who pays as usual) and DSO (who collects zero revenue for any energy trading within the Microgrid) sides.

It is therefore quite obvious that the suggested selectivity benefit levels on consumer side and on MS side **cannot** be achieved simultaneously—in actual fact, reaching the full extent of one index will inevitably reduce the other one to zero. In addition, the calculated benefits due to local retail market are expected to be shared not just between consumer and MS units, but also with DSO as a potential interest holder.

Nonetheless, the selectivity benefit index serves as a good indication of potential MS profitability as actual MS profits are likely to be proportional to this value despite changes in grid condition, tariff structure, as well as policy settings. In this sense, investment decision in an unsubsidized MS unit is only economically reasonable when calculated selectivity benefit value on MS side is positive—the actual profitability and investment return speed, however, can only be determined after clear knowledge of interest allocation model within a Microgrid.

5.4.2 Technical Benefit Indices

Reliability improvement credits of Microgrid can be seen as independent from normal daily operation routines and have been analyzed separately in section 2.2.4, thus they are not discussed in detail here.

5.4.2.1 Reduction of Peak Loading

Reduction of Peak Loading RPL (DSO perspective) refers to reduction of peak thermal loading in worst loaded element(s) under Microgrid operation when compared to the passive grid case without Microgrid. It is defined as relative values as follows:

RPL (%) = 1 – peaking loading in Microgrid / peak loading in passive grid

In Figure 5-21, a sample definition is given based on histogram view.

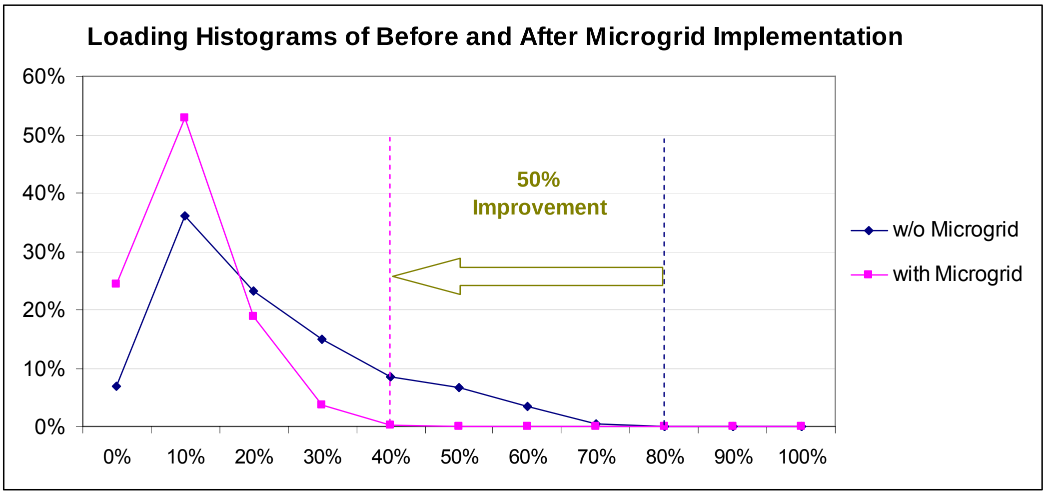


Figure 5-21 Definition of Peak Loading Reduction Index

5.4.2.2 Reduction of Voltage Variation

Reduction of Voltage Variation RVV (DSO perspective) refers to reduced max absolute voltage deviation at worst voltage quality node(s) under Microgrid operation when compared to the passive grid case without Microgrid. It is defined as relative values as follows:

RPL (%) = 1 – max absolute voltage variation in Microgrid / max voltage in passive grid

In Figure 5-22, a sample definition is given based on histogram view.

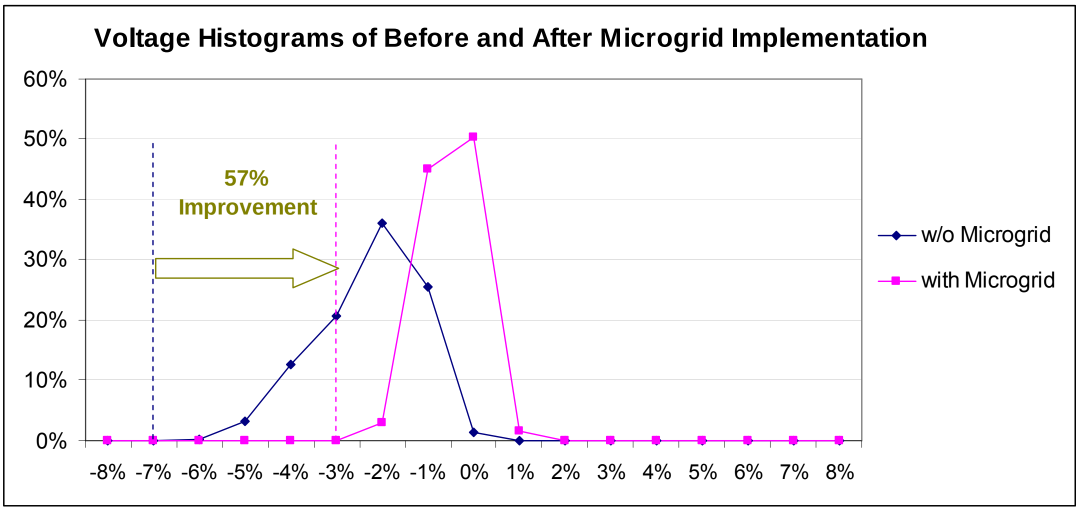


Figure 5-22 Definition of Voltage Variation Reduction Index

5.4.2.3 Reduction of System Loss

Reduction of System Loss RSL (DSO perspective) refers to reduction of annual energy loss under Microgrid operation when compared to the passive grid case without Microgrid. It is defined as relative values as follows:

RSL (%) = 1 – annual energy loss in Microgrid / annual energy loss in passive grid

In Figure 5-23, a sample definition is given for the loss reduction index.

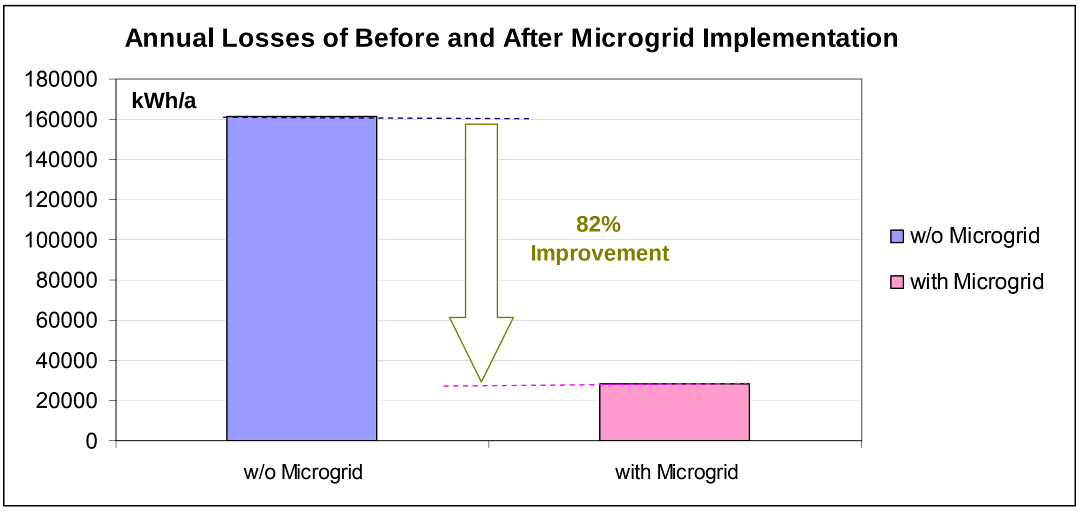


Figure 5-23 Definition of System Loss Reduction Index

5.4.3 Environmental Benefit Index

5.4.3.1 Total Emission Reduction

Total Emission Reduction TER (regulator perspective) refers to the reduction of GHG emission level per kWh consumption in a Microgrid when compared to the passive grid case without Microgrid. It can be defined either as relative value (%) or absolute value (€/kWh) as follows:

TER (p.u.) = 1 – GHG emission level in Microgrid / national GHG emission level (passive case)

TER (kg/kWh) = national GHG emission level (passive case) – GHG emission level in Microgrid

Although SO_2, NO_x and particle matter emission reductions are also expected from Microgrid operation, there are currently no explicit trading platforms within Europe as the European ETS market, thus reduction effects under these criteria can be viewed largely as by–products of GHG emission control.

6 Methodology for Simulation and Analysis

6.1 Overview of Micro Source Dispatch in a Microgrid

One key argument towards Microgrid conversion is the potential controllability it could bring about to an otherwise passive grid. It is understood inherently in scope of this report that such controllability will mainly depend on dispatchable MS units, which, as already shown in section 5.2.3, will feature a quadratic cost model (as also normally applied for central thermal units). In Figure 6-1, the quadratic cost curves of 10 sample MS units are shown first as a reference.

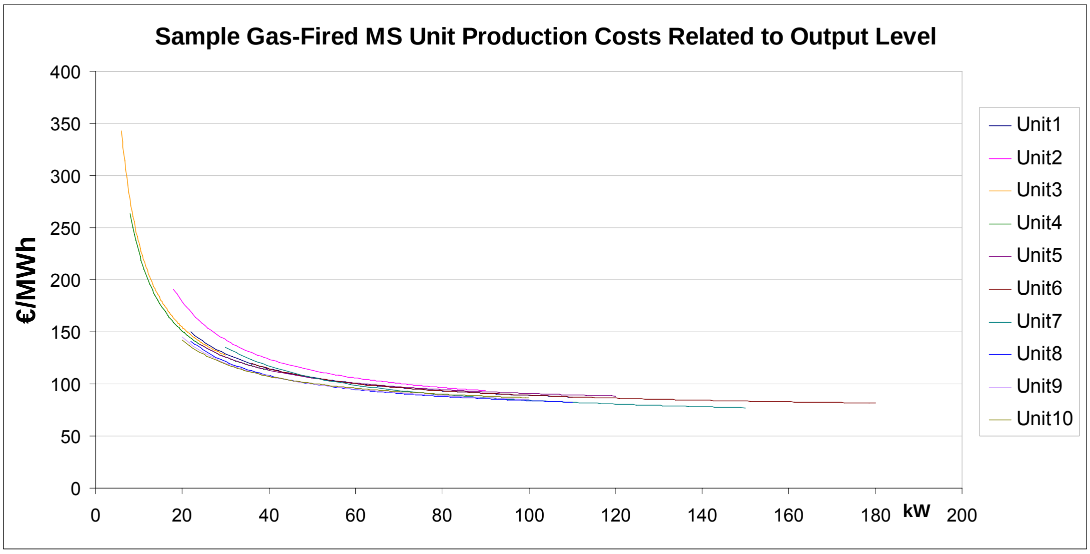


Figure 6-1 Sample Cost Curves of 10 Dispatchable MS Units

Similar to the unit commitment problem on transmission level, a Microgrid operator will be faced with the task of scheduling available MS units so as to maximize opportune profit or minimize opportune cost. When only economic concerns are involved (and not considering switching costs), this scheduling task can be solved as a standard MIQP (mixed integer quadratic programming) problem with a non-linear solution space. In Figure 6-2, a sample series of dispatch decisions are shown for the 10-unit problem given by Figure 6-1.

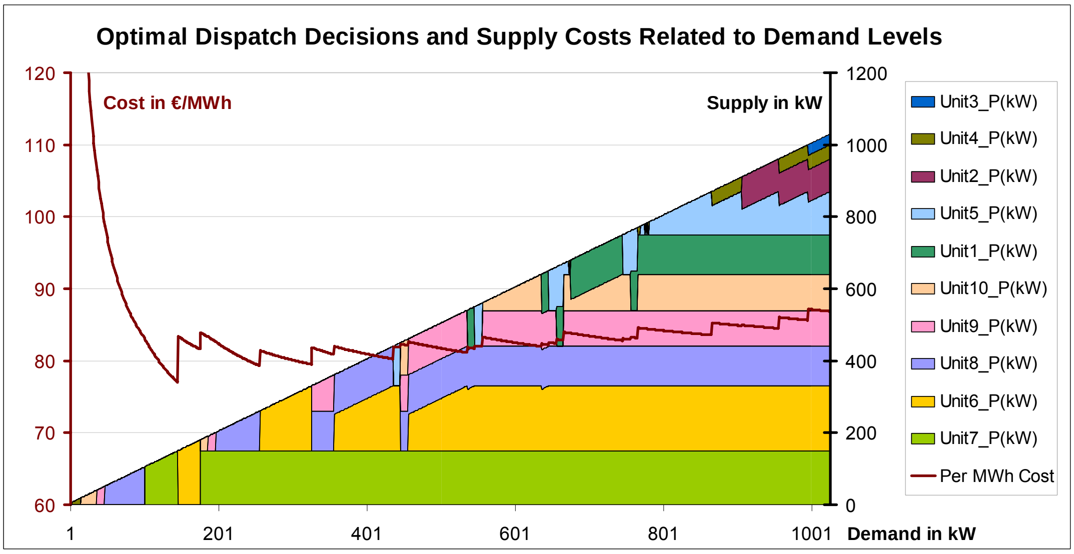


Figure 6-2 Sample Optimal Dispatch Decisions and Total Costs under Economic View

Although Figure 6-2 has suggested a quite straightforward solution to the Microgrid scheduling problem, it only serves as the theoretical optimum. In reality, the unique market and network settings of Microgrids will add extra dimensions to this task, as shown by the following examples:

The Impact of Directional Pricing

In Figure 6-3, the opportune profit (positive y axis) / losses (negative y axis) curves per sample hour of a Microgrid is plotted against total unit output level based on the dispatch decisions from Figure 6-2. A uniform pricing condition (90 €/MWh) and a directional pricing condition (90 €/MWh for import and 50 €/MWh for export) are compared under 600 kW load demand level. Obviously, the directional pricing scheme has created an economic island, which forces MS units to generate at a lower output level and obtain a comparatively lower profit than the uniform pricing case. Generally it can be stated:

(1) When MS generation is lower than load demand, then Microgrid is importing for the part of load not supplied by MS:

Opportune profit of a Microgrid is the difference between import cost (virtual sense) and MS generation cost (actual sense) for the part of self-supplied energy--when MS cost is higher than import cost, the calculated value will be negative and leads to opportune loss.

(2) When MS generation exceeds load demand, then Microgrid is exporting excess MS energy to upstream network:

Opportune profit of the Microgrid is the sum of [1] difference of import and MS costs for supplying local load demand (as defined in the former case), and [2] sales profit for (export revenue minus MS cost) exported energy. When the export price is lower than MS cost, then the opportune profit curve will start to have decreasing values as soon as MS generation exceeds load demand.

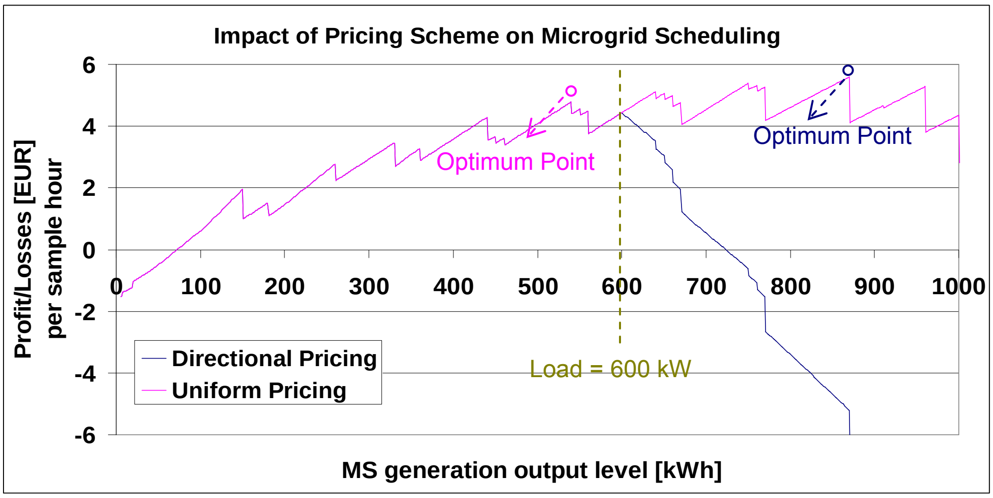


Figure 6-3 Impact of Directional Pricing on Microgrid Scheduling Decisions

The Impact of Network Constraints

Figure 6-4 shows two opportune profit/loss curves based on pure economic mode and a combined mode with consideration of technical constraints. By setting load demand at 500 kW level and assuming directional pricing scheme (i.e. economic island), the Microgrid is forced to operate at a sub-optimal (economically) dispatch point so as to maintain one or more technical criteria (voltage and/or line loading) within boundaries.

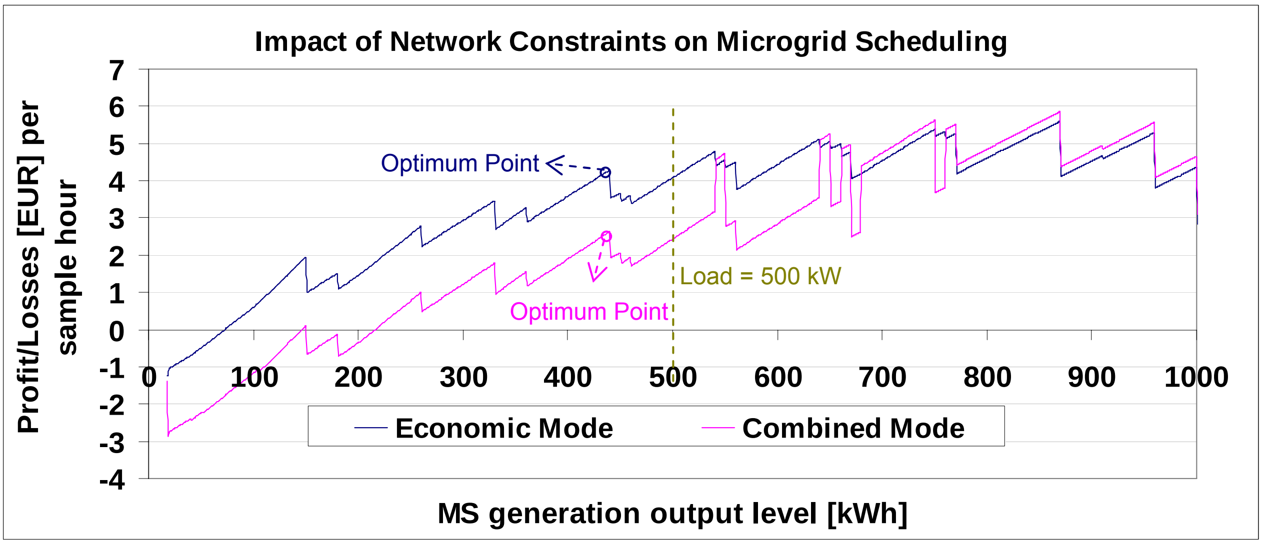


Figure 6-4 Impact of Network Constraints over Microgrid Scheduling Task

6.2 Description and Layout of the Microgrid Scheduling Task

The analysis of the different Microgrid optimal operation strategies illustrated above is carried out on a yearly basis using sequential Monte Carlo simulation method, as shown by Figure 6-5. Due to the cyclic nature of both electricity market price and renewable (e.g. photovoltaic) output, intraday Microgrid schedules are created and evaluated as hourly settlement results. Annual outcome of the optimization algorithm is consequently a statistical summary of individual daily simulations.

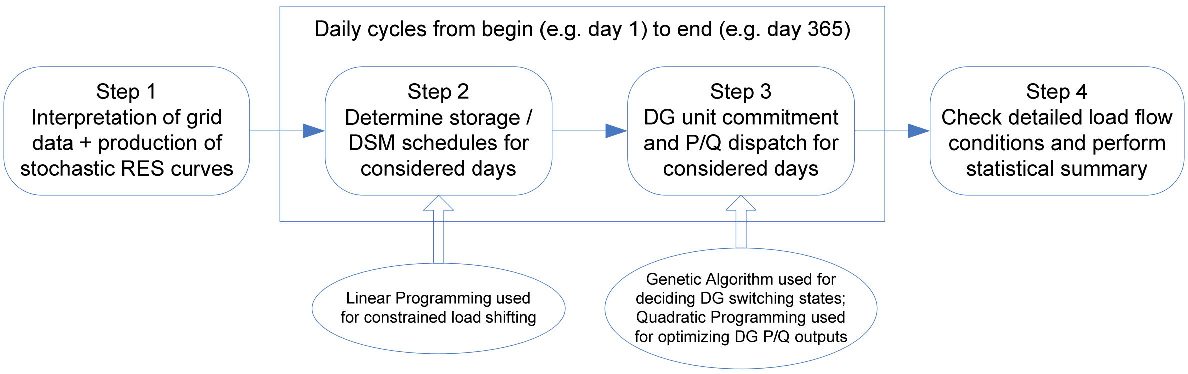


Figure 6-5 Microgrid Scheduling

For preparation of the scheduling task, typical annual profiles of load, RES generation, and market price need to be created based on measurement or historical data. As Microgrids are typically located at LV level with dominant small residential or commercial customers, there are significant variations in load curves, which, in combination with the uncertainties from RES output as well as wholesale electricity price, place the day-ahead Microgrid scheduling task under a highly stochastic environment. Since prediction errors are inevitable, potential Microgrid benefits evaluated from simulated or forecasted data should be viewed as best-case results—i.e., actual operation decisions might be sub-optimal, thus leading to lower benefits.

In order to deal with the modelling requirements of different types of DER units, the cycling daily dispatch procedures are divided into two sub-steps: firstly the DER units with timeline constraints (i.e. storage and dispatchable loads) are dispatched with priority, and then the DG unit schedules are created respectively for active and reactive powers. For optimization of storage and dispatchable MS units, linear programming technique is applied; while DG scheduling uses genetic algorithm as an outer shell to determine optimal DG on/off states and quadratic / linear programming models to estimate load flows in the studied networks.

After creation of a complete schedule, actual load flow states are examined to finalize total energy loss as well as voltage and loading conditions in the network so as to offset estimation errors. Due to the large amount of data output, network variables need to be recorded as discrete probability density functions via a statistical summary procedure.

The following sections place emphasis on the daily dispatch procedure shown as step 2 and step 3 in Figure 6-5, and combined dispatch mode is used as an example to illustrate the scheduling approach.

6.3 Definition of Microgrid Scheduling Task as an Optimisation Problem

If a cost function is assigned to GHG emissions as well as to certain technical aspects such as losses or reliability of supply, such external factors can be internalized within the economic criteria, leading to an economic formulation of the optimal control strategy problem. Thus, let us introduce the Microgrid operational objective function *G*, expressed in terms of total opportune profit (or opportune loss when negative) as from the combination of individual cost/revenue entries:

$$G = (r_{retail} + r_{msell}) - (f_{mbuy} + f_{dgen} + f_{switch} + f_{emission} + f_{loss} + f_{RES} + f_{ICT}) \qquad (6\text{-}1)$$

Consider a Microgrid with *I* DG units, *J* load points, *K* network nodes, and *N* network link components (namely, transformers and circuits) under *T* time steps (*T*=24 for a day), where:

- r_{retail} is the total retail revenue collected from end customers;
- r_{msell} is the total revenue of selling electricity to wholesale market: $r_{msell} = \sum_{t=1}^{T} r_{msell}^{t}$;
- f_{mbuy} is the total cost of buying electricity from wholesale market (-): $f_{mbuy} = \sum_{t=1}^{T} f_{mbuy}^{t}$;
- f_{dgen} is the overall generation cost of DG (fuel and O&M cost): $f_{dgen} = \sum_{t=1}^{T}\sum_{i=1}^{I} f_{dgen}^{i,t}$;
- f_{switch} is the overall cost relevant to switching operation of DG (that wears out the units, shortens their useful life and increases maintenance cost): $f_{switch} = \sum_{t=1}^{T}\sum_{i=1}^{I} f_{switch}^{i,t}$;
- $f_{emission}$ is the total emission cost from electricity generation: $f_{emission} = \sum_{t=1}^{T}\sum_{i=1}^{I} f_{emission}^{i,t}$;
- f_{loss} is total cost of energy losses in the grid: $f_{loss} = \sum_{t=1}^{T} f_{loss}^{t}$;
- f_{RES} is the total cost of electricity generated from RES units;
- f_{ICT} is the total control and communication costs for operating the Microgrid.

The total opportune profit *G* is obviously an artificial entry in a liberalized electricity market, as it represents the interests of multiple entities and requires extensive collaboration and compromise in reality. For consideration of Microgrid scheduling, r_{retail}, $f_{RES,}$ and f_{ICT} entries are comparatively constant variables that can be decoupled from the scheduling task, which means it is sufficient to only consider r_{msell}, f_{mbuy}, f_{dgen}, f_{switch}, $f_{emission}$ and f_{loss}, for the optimization problem. Therefore, the general optimization problem hour by hour (or in case with different time accuracy) can be expressed as equation (6-2):

$$
\begin{array}{l}
\max G \\
\text{s.t.}\quad \forall\, i \in [1, I],\ \ j \in [1, J],\ \ k \in [1, K],\ \ n \in [1, N],\ \ t \in [1, T] \\
\text{Constraint 1) Energy Balances:} \\
\begin{cases}
\sum_{i=1}^{I} S_t^i \cdot P_{dgen}^{i,t} - \sum_{j=1}^{J} P_{demand}^{j,t} + P_{mbuy}^t - P_{msell}^t - P_{loss}^t = 0 \\
\sum_{i=1}^{I} S_t^i \cdot Q_{dgen}^{i,t} - \sum_{j=1}^{J} Q_{demand}^{j,t} + Q_{mbuy}^t - Q_{msell}^t - Q_{loss}^t = 0
\end{cases} \\
\text{Constraint 2) DG Physical Limits:} \\
\begin{cases}
\text{Min On/Off Duration:} & \begin{cases} T_{on}^{i,t} \ge T_{on\min}^i \\ T_{off}^{i,t} \ge T_{off\min}^i \end{cases} \\
\text{Max/Min Output:} & P_{\min}^i \le P^{i,t} \le P_{\max}^i,\quad Q_{\min}^i \le Q^{i,t} \le Q_{\max}^i
\end{cases} \\
\text{Constraint 3) Network Technical Limits:} \\
\begin{cases}
\text{Voltage Band:} & U_{\min}^k \le U^{k,t} \le U_{\max}^k \\
\text{Component Loading:} & I^{n,t} \le I_{th}^n
\end{cases}
\end{array}
\qquad (6\text{-}2)
$$

- S as DG on (1) / off (0) state;
- P_{dgen} as DG output power;
- P_{demand} as power demand from load, RES, storage, and DSM;
- P_{mbuy} as bought power;
- P_{msell} as sold power;
- P_{loss} as total grid power loss;

(Q entries are defined similarly)

- $T_{on,min}$ as minimum duration for continuous DG on-state;
- $T_{off,min}$ as minimum duration for continuous DG off-state;
- P_{max}/P_{min} as max/min output limits of DG active power;
- Q_{max}/Q_{min} as max/min output limits of DG reactive power;
- U_{max}/U_{min} as max/min voltage

In particular, three sets of system operational constraints have been identified, namely:

1) Active and reactive energy balances in the Microgrid and with the upstream network;
2) DG physical constraints, regarding to minimum on and off operation time (thermal constraints) and minimum and maximum energy outputs;
3) Network constraints, referring to voltage band limits and component (transformers and circuits) thermal limits.

Further details are explained throughout the sequel.

6.4 Storage / Load Dispatch via Linear Programming

In Microgrids, a storage unit can be owned by a DSO to provide balancing or other services, or by a energy supplier to offset renewable variations from its generation portfolio, or by an end consumer to realize dispatchable MS control—specifically, when investment and operation costs of a storage technology reach down to a sufficiently low level, the most commercially justifiable application of storage unit in a grid-connected Microgrid will be a simple price arbitrager model. Regardless of ownership difference, an arbitrager storage unit will always be operated according to daily market price development so as to maximize opportune profit or minimize opportune loss, as shown by the linear programming problem in equation (6-3).

$$Minmize \quad h = \sum_{t=1}^{T} \left[q_t \cdot \left(x_t - y_t \right) + k_x \cdot x_t + k_y \cdot y_t \right]$$

$$So\ that: \quad \forall\ t \in [1, T], \quad Define\ E_t = E_{\text{int}} + \eta \cdot \sum_{v=1}^{t} x_v - \sum_{v=Tb}^{t} y_v - l \cdot t \qquad (6\text{-}3)$$

$$\begin{cases} 0 \le x_t \le PX_{\max}, \quad 0 \le y_t \le PY_{\max}, \\ E_{\min} \le E_t \le E_{\max} \\ E_T = E_{end} \end{cases}$$

where:

- h is the total operating loss (+) or profit (-) of the storage unit in considered day;
- x_t is the amount of purchased energy (i.e. storage unit is charged) in period t;
- y_t is the amount of sold energy (i.e. storage unit is discharged) in period t;
- q_t is the market electricity price in period t;
- k_x is the per-kWh charging cost, k_y is the per-kWh discharging cost of storage unit;
- η is the energy conversion efficiency for charging the storage unit;
- l is the amount of standby energy loss of storage unit in a defined period (one hour);
- PX_{max} is the maximum charging power, PY_{max} is the maximum discharging power;
- E_{min} is the minimum storage energy level, E_{max} is the maximum storage energy level;
- E_{int} is the initial energy level in a day, E_{end} is the ending energy level in a day;

In equation (6-3), the storage unit is operated with a constant daily cycle—i.e., its state of charge starts as 50% at begin of day (typically at midnight) and is expected to end up also with 50% by the end of day. The maximum / minimum energy levels correspond solely to the capacity rating of the storage unit, while the maximum charging / discharging powers reflect both internal peak current settings of the storage unit and external limits (such as thermal current rating of a neighbouring line) from the grid. Although an arbitrager storage unit can appear in many different technological forms, the linear programming model from equation (6-3) should be sufficient for evaluating best-case outcome (i.e. when compared to dynamic programming or stochastic programming ---for all potential setups.

In scope of this deliverable, the arbitrager storage application is assumed to be a single device allocated to Microgrid infeed point so as to facilitate voltage / frequency control when the Microgrid enters island mode of operation—however, the arbitrager model will be no longer applicable under island mode, where energy balancing becomes the only operational aim. In the mean time, the linear programming model in equation (6-3) can also be simplified to model dispatchable load behaviour by neglecting efficiency and maximum / minimum energy level constraints. For this case, shifted and interrupted loads are differentiated by if total daily demand is kept.

6.5 Cost, Emission and Network Modelling via Quadratic Programming

6.5.1 Definition and Combination of Individual Cost and Revenue Entries

Most cost entries in equation (6-1) used for Microgrid scheduling task are calculated on the basis of the on/off status (which is decided by the genetic algorithm) and active power outputs (which is determined by a sub-dispatch via quadratic programming) of DG units as equation (6-4):

$$
\begin{aligned}
& f_{mbuy}^{t} = q_t \cdot P_{mbuy}^{t}; \quad r_{msell}^{t} = q_t \cdot P_{msell}^{t} \\
& f_{dgen}^{i,t} = S_t^i \cdot \left(a^i \cdot P_{dgen}^{i,t\,2} + b^i \cdot P_{dgen}^{i,t} + c^i \right) \\
& f_{switch}^{i,t} = S_t^i \cdot (1 - S_{t-1}^i) \cdot k_{off}^i \cdot \left[1 - \exp(-T_{off}^{i,t} / T_{off\_\min}^i) \right] \\
& f_{emission}^{i,t} = S_t^i \cdot k_{GHG}^i \cdot P_{dgen}^{i,t} \\
& f_{loss}^{t} = k_{loss} \cdot P_{loss}^{t}
\end{aligned}
\tag{6-4}
$$

where, for each DG unit *i* out of the total units *I*, and for each hour *t* out of *T(=24)* in a day:

- S_t^i is the specific DG switching state (0/1 for off/on state, respectively) in period *t*;
- q_t is the market price of electricity in period *t*;
- P_{mbuy}^{t} is purchased electric power, P_{msell}^{t} is sold electric power in period *t*;
- $P_{dgen}^{i,t}$ is the active power output from DG unit *i* in hour *t*.
- k_{off}^{i} is the cold start-up cost of DG unit *i*; k_{loss} is the average loss cost per kWh;
- k_{GHG}^{i} is the external GHG emission cost per kWh generation for DG unit *i*;
- $T_{off\_\min}^{i}$ is minimum cool-off time for DG *i*, $T_{off}^{i,t}$ is actual cool-off time at period *t*;

According to energy balance equations in (6-2), the total amount of hourly on-site generated electricity and traded (i.e. bought and sold) electricity should be equal to power loss plus total power demand from load, RES, storage, and dispatchable MS. Thus r_{mbuy}, f_{msell}, f_{dgen}, $f_{emission}$ and f_{loss} can be combined into one function $f_{combine}$ as a quadratic formulation of DG active power output plus a linear formulation of power loss in the grid once DG switching states are determined:

$$
\begin{aligned}
f_{combine} &= \left(f_{mbuy} - r_{msell} \right) + f_{dgen} + f_{emission} + f_{loss} \\
&= \sum_{t=1}^{T} \left[q_t \cdot \left(P_{mbuy}^{t} - P_{msell}^{t} \right) + \sum_{i=1}^{I} S_t \cdot \left(a^i \cdot P_{dgen}^{i,t\,2} + b^i \cdot P_{dgen}^{i,t} + c^i \right) + \sum_{i=1}^{I} S_t^i \cdot k_{GHG}^i \cdot P_{dgen}^{i,t} + k_{loss} \cdot P_{loss}^{t} \right] \\
&= \sum_{t=1}^{T} \left[q_t \cdot \left(\sum_{j=1}^{J} P_{demand}^{j,t} + P_{loss}^{t} - \sum_{i=1}^{I} S_t \cdot P_{dgen}^{i,t} \right) + \sum_{i=1}^{I} S_t \cdot \left(a^i \cdot P_{dgen}^{i,t\,2} + \left(b^i + k_{GHG}^i \right) \cdot P_{dgen}^{i,t} + c^i \right) + k_{loss} \cdot P_{loss}^{t} \right] \\
&= \sum_{t=1}^{T} \sum_{i=1}^{I} S_t \cdot \left(a^i \cdot P_{dgen}^{i,t\,2} + \left(b^i + k_{GHG}^i - q_t \right) \cdot P_{dgen}^{i,t} + c^i \right) + \sum_{t=1}^{T} \left[\left(k_{loss} - q_t \right) \cdot P_{loss}^{t} \right] + \sum_{t=1}^{T} \left[q_t \cdot \sum_{j=1}^{J} P_{demand}^{j,t} \right] \\
&= KP_{quad}(P_{dgen}) + KL_{linear}(P_{loss}) + K_{const}
\end{aligned}
\tag{6-5}
$$

Since it is possible to express grid power loss as a quadratic function of active and reactive power outputs of DG, eventually all cost / revenue entries except for f_{switch} can be combined into a uniform continuous quadratic model once DG switching states are known. Therefore, a sub-problem of Microgrid scheduling can be created using this partial objective function (no f_{switch}) together with all constraints from (6-2) except for minimum on/off duration limits. Thus Microgrid schedules can be created by applying a meta-heuristic algorithm to binary DG switching state codes that can be iteratively evaluated by solving this sub-problem.

6.5.2 Load Flow Estimation Techniques

A linearised load flow method based on backward / forward sweep principle was developed to obtain a fast estimation of active / reactive power flows in link components based on nodal injection and extraction values (for more details see Annex 2). Instead of using loop break-points the adopted algorithm tracks down a minimum loop set and apply voltage equilibrium conditions within each loop to assemble sufficient linear equations for solving the load flow. As (6-6) has been formulated as a real-number problem, standard linear solver techniques can be applied to extract estimation coefficients when nodal or DG active / reactive powers are taken as inputs.

$$\begin{bmatrix} \vec{p}_{node} \\ \vec{q}_{node} \\ \vec{u}_{mesh} \\ \vec{\alpha}_{mesh} \end{bmatrix} = \begin{bmatrix} \vec{T}_{LtN} & \vec{0} \\ \vec{0} & \vec{T}_{LtN} \\ \vec{R}/\vec{U} & \vec{X}/\vec{U} \\ \vec{X}/\vec{U}^2 & -\vec{R}/\vec{U}^2 \end{bmatrix} \cdot \begin{bmatrix} \vec{p}_{link} \\ \vec{q}_{link} \end{bmatrix} = \vec{M} \cdot \begin{bmatrix} \vec{p}_{link} \\ \vec{q}_{link} \end{bmatrix}$$

$$\Rightarrow \begin{bmatrix} \vec{p}_{link} \\ \vec{q}_{link} \end{bmatrix} = \vec{M}^{-1} \cdot \begin{bmatrix} \vec{p}_{node} \\ \vec{q}_{node} \\ \vec{u}_{mesh} \\ \vec{\alpha}_{mesh} \end{bmatrix} = \vec{A}_n \cdot \begin{bmatrix} \vec{p}_{node} \\ \vec{q}_{node} \end{bmatrix} + \vec{B}_n \tag{6-6}$$

$$= \vec{A}_d \cdot \begin{bmatrix} \vec{p}_{dgen} \\ \vec{q}_{dgen} \end{bmatrix} + \vec{B}_d$$

- p_{node}/q_{node} as nodal active / reactive power vectors;
- p_{link}/q_{link} as link active / reactive power vectors;
- p_{dgen}/q_{dgen} as DG active / reactive power vectors;
- u_{mesh}/α_{mesh} as meshed voltage magnitude / angle constants;
- T_{LtN} as link to node deduction matrix of grid topology;
- R / X as meshed link resistance / reactance vectors;
- U as meshed nodal voltage vector;

Based on the knowledge of estimated link power flow (an equivalent backward sweep) from equation (6-6), component (current) loading level, nodal voltage magnitude and total grid power loss can be further deducted as linear or quadratic functions of DG active / reactive power outputs. In (6-7), the resulting forms of load flow estimation coefficients for current, voltage, and loss terms are respectively presented. It can be seen that total power loss and the square of component current loading can be expressed in quadratic forms of DG power vector, while nodal voltage magnitudes can be estimated through linear formulas.

$$Write\ \vec{x} = \begin{bmatrix} \vec{p}_{dgen}^T & \vec{q}_{dgen}^T \end{bmatrix}^T, \quad then:$$

$$\Rightarrow \vec{i}_{link} = \vec{K}_i \cdot \sqrt{\vec{p}_{link}^2 + \vec{q}_{link}^2}$$

$$= \sqrt{\left(\vec{A}_{ip} \cdot \vec{x} + \vec{B}_{ip}\right)^2 + \left(\vec{A}_{iq} \cdot \vec{x} + \vec{B}_{iq}\right)^2}$$

$$\Rightarrow \vec{u}_{node} = \vec{D}_{volt} \cdot \Delta\vec{u}_{link} + \vec{K}_{volt} = \vec{D}_{volt} \cdot \left(\vec{A}_{du} \cdot \vec{x} + \vec{B}_{du}\right) + \vec{B}_{du} \tag{6-7}$$

$$= \vec{A}_u \cdot \vec{x} + \vec{B}_u$$

$$\Rightarrow p_{loss} = \sum_{n=1}^{N} \Delta p_{link}^n = \sum_{n=1}^{N} \left(\vec{x}^T \cdot \vec{A}_{dp}^n \cdot \vec{x} + \vec{B}_{dp}^n \cdot \vec{x} + \vec{C}_{dp}^n\right)$$

$$= \vec{x}^T \cdot \vec{A}_l \cdot \vec{x} + \vec{B}_l \cdot \vec{x} + \vec{C}_l$$

- p_{link}/q_{link} as link active / reactive power vectors;
- p_{dgen}/q_{dgen} as DG active / reactive power vectors;
- i_{link} as thermal loading vector of all link components;
- u_{node} as nodal voltage magnitude vector;
- Δu_{link} as link voltage difference vector;
- p_{loss} as total grid power loss;
- Δp_{link} as link power loss vector;

It should be noted that the estimation coefficient vectors (*A*, *B*, *C*, etc.) in equation (6-7) are dependent on actual (or estimated) voltage and loss values, thus estimation accuracy of linear / quadratic models proposed above will be heavily influenced by an initial guess of potential network states. However, the estimation errors can be gradually eliminated under an iterative evaluation framework, which can produce much more accurate results at the cost of higher computational efforts.

6.5.3 Decoupled P and Q Sub-Dispatch Processes

Based on models of chapter 6.5.1 and 6.5.2, the definite-state DG dispatch sub-problem can be solved under a quadratic programming framework shown by eq. (6-8). Due to considerations of both computational complexity and the non-linearity of thermal loading constraints, the problem needs to be decoupled into an active power (*P*) dispatch step and a reactive (*Q*) power dispatch step. Such a decoupling also facilitates actual control and trading implementations.

$$\begin{aligned}
&\forall \quad k\in[1,K],\ n\in[1,N], \quad write\ \ \vec{p}=\vec{p}_{dgen},\ \vec{q}=\vec{q}_{dgen}, \quad then:\\
&\min: f_{combine}=\left(f_{mbuy}-r_{msell}\right)+f_{dgen}+f_{emission}+f_{loss}=KP_{quad}(\vec{p})+KQ_{quad}(\vec{q})+K_{const}\\
&s.t.\quad \begin{cases}\vec{p}_{\min}\le\vec{p}\le\vec{p}_{\max}, \quad \vec{q}_{\min}\le\vec{q}\le\vec{q}_{\max}\\ U^k=\vec{a}_{u_p}\cdot\vec{p}+\vec{a}_{u_q}\cdot\vec{q}+b_u, \quad U_{\min}\le U^k\le U_{\max}\\ I^n=\sqrt{\left(\vec{a}_{ip_p}\cdot\vec{p}+\vec{a}_{ip_q}\cdot\vec{q}+b_{ip}\right)^2+\left(\vec{a}_{iq_p}\cdot\vec{p}+\vec{a}_{iq_q}\cdot\vec{q}+b_{iq}\right)^2}=\sqrt{I_p^{\ 2}+I_q^{\ 2}}\le I_{th}\end{cases}\\
&with\ \ \vec{a}_{ip_p}\cdot\vec{p}>>\vec{a}_{ip_q}\cdot\vec{q}, \quad \vec{a}_{iq_q}\cdot\vec{q}>>\vec{a}_{iq_p}\cdot\vec{p}
\end{aligned} \tag{6-8}$$

Firstly, DG real power is dispatched according to (6-9). Potential reactive power output from DG is either supposed to be capable of relieving grid constraints (optimistic option), or contrarily assumed to further exacerbate existing constraints (pessimistic option). As the optimistic mode could potentially lead to unmet technical constraints in the step of reactive power dispatch, pessimistic assumptions are normally taken to ensure algorithm convergence.

$$\begin{aligned}
&\min: KP_{quad}(\vec{p}), \quad s.t.\quad \begin{cases}\vec{p}_{\min}\le\vec{p}\le\vec{p}_{\max}\\ \left(U_{\min}-b_u\right)-\vec{a}_{u_q}\cdot\vec{q}\le\vec{a}_{u_p}\cdot\vec{p}\le\left(U_{\max}-b_u\right)-\vec{a}_{u_q}\cdot\vec{q}\\ \left(\vec{a}_{ip_p}\cdot\vec{p}+b_{ip}\right)^2+\left(\vec{a}_{iq_q}\cdot\vec{q}+b_{iq}\right)^2\le I_{th}^{\ 2}\end{cases}\\
&Optimistic:\ \begin{cases}\left(U_{\min}-b_u\right)-Max\left(\vec{a}_{u_q}\cdot\vec{q}\right)\le\vec{a}_{u_p}\cdot\vec{p}\le\left(U_{\max}-b_u\right)-Min\left(\vec{a}_{u_q}\cdot\vec{q}\right)\\ -\sqrt{I_{th}^{\ 2}-Min\left(\vec{a}_{iq_q}\cdot\vec{q}+b_{iq}\right)^2}-b_{ip}\le\vec{a}_{ip_p}\cdot\vec{p}\le\sqrt{I_{th}^{\ 2}-Min\left(\vec{a}_{iq_q}\cdot\vec{q}+b_{iq}\right)^2}-b_{ip}\end{cases}\\
&Pessimistic:\begin{cases}\left(U_{\min}-b_u\right)-Min\left(\vec{a}_{u_q}\cdot\vec{q}\right)\le\vec{a}_{u_p}\cdot\vec{p}\le\left(U_{\max}-b_u\right)-Max\left(\vec{a}_{u_q}\cdot\vec{q}\right)\\ -\sqrt{I_{th}^{\ 2}-Max\left(\vec{a}_{iq_q}\cdot\vec{q}+b_{iq}\right)^2}-b_{ip}\le\vec{a}_{ip_p}\cdot\vec{p}\le\sqrt{I_{th}^{\ 2}-Max\left(\vec{a}_{iq_q}\cdot\vec{q}+b_{iq}\right)^2}-b_{ip}\end{cases}
\end{aligned} \tag{6-9}$$

As a second step, DG reactive power is dispatched according to the previous active power allocation results, as shown by (6-10). It should be noted that all cost / revenue entries except for power loss cost in equation (6-4) currently relates only to DG active power output, while in reality DG reactive power output will influence DG efficiency and thus hold impacts over generation and emission costs as well.

$$\min: KQ_{quad}(\vec{q}), \quad s.t.\quad \begin{cases}\vec{q}_{\min}\le\vec{q}\le\vec{q}_{\max}\\ \left(U_{\min}-b_u\right)-\vec{a}_{u\_p}\cdot\vec{p}\le\vec{a}_{u\_q}\cdot\vec{q}\le\left(U_{\max}-b_u\right)-\vec{a}_{u\_p}\cdot\vec{p}\\ -\sqrt{I_{th}^{\ 2}-\left(\vec{a}_{ip\_p}\cdot\vec{p}+b_{ip}\right)^2}-b_{iq}\le\vec{a}_{iq\_q}\cdot\vec{q}\le\sqrt{I_{th}^{\ 2}-\left(\vec{a}_{ip\_p}\cdot\vec{p}+b_{ip}\right)^2}-b_{iq}\end{cases} \tag{6-10}$$

When the quadratic programming problem arrives at a non-convergent solution, the voltage and loading constraints will be relaxed bit by bit until a convergent solution is found.

6.6 Genetic Algorithm-Based DG Unit Commitment

As the outer layer of scheduling program, the genetic algorithm (GA) serves two main purposes: it creates DG on/off schedules (i.e. 'individuals') that are used as input data of sub-dispatch procedures illustrated in 6.5, and then it collects return values of objective function and constraint violation status to compare the fitness of all individuals in an examined generation. A sample 'individual' can be seen from Figure 6-6 which is a binary matrix dimensioned by DG count and total time steps.

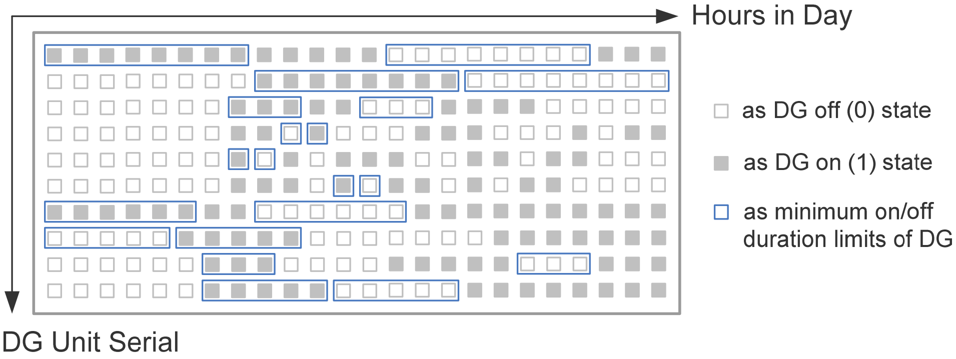


Figure 6-6 Sample 10-DG switching schedule for a considered day

During initialization of the genetic algorithm, a certain number of individuals are randomly created to form the first generation of 'population'. It should be noted, however, that each random individual strictly follows minimum on/off duration limits—as suggested by Figure 6-6—to ensure a good starting point for the 'gene pool'.

As soon as an individual is created, a sub-dispatch routine will be called to examine the economic, technical, and environmental performances of this switching scheme. Resulting objective function value will be combined with switching cost to form total profit or loss, while voltage / loading violations and on / off duration violations (if applicable) will be both converted into penalty factors. Sum of total profit /loss and all penalty factors provide the eventual fitness of examined individual.

In Figure 6-7, a simplified cross-over operation is illustrated: it can be seen that adopted cross-over behaviour does not change DG on / off durations from either side of parents.

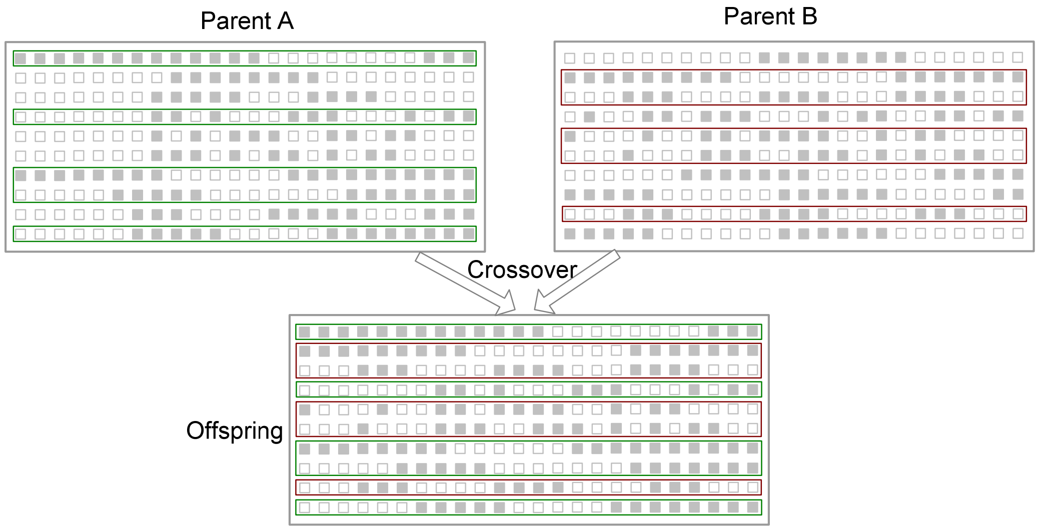


Figure 6-7 Sample Cross-Over Operation

Due to the relatively small changes made by cross-over operator, two mutation mechanisms are introduced to the customized genetic algorithm, as shown by Figure 6-8. A block mutation operator will attempt to randomly combine short time segments into a longer one or do vice versa, while a boarder mutation operator will randomly attempt to shorten, prolong, or shift a certain time segment.

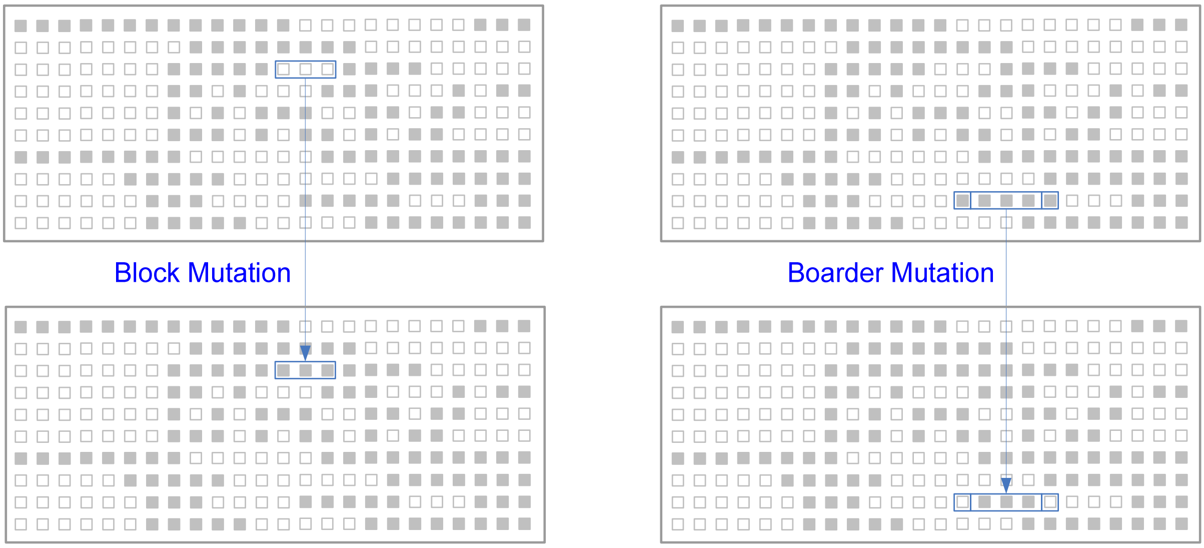


Figure 6-8 Sample Mutation Operations

In addition to cross-over and mutation operation, both elitism and replacement of worst-performing individuals are added to the algorithm. In Figure 6-9, the convergence behaviour of this genetic algorithm is exemplified with a sample 10-unit system. The initial steep decrease of total cost corresponds to the fast elimination of individuals with violated constraints (that lead to high penalties), after which slower improvement of fitness value is expected.

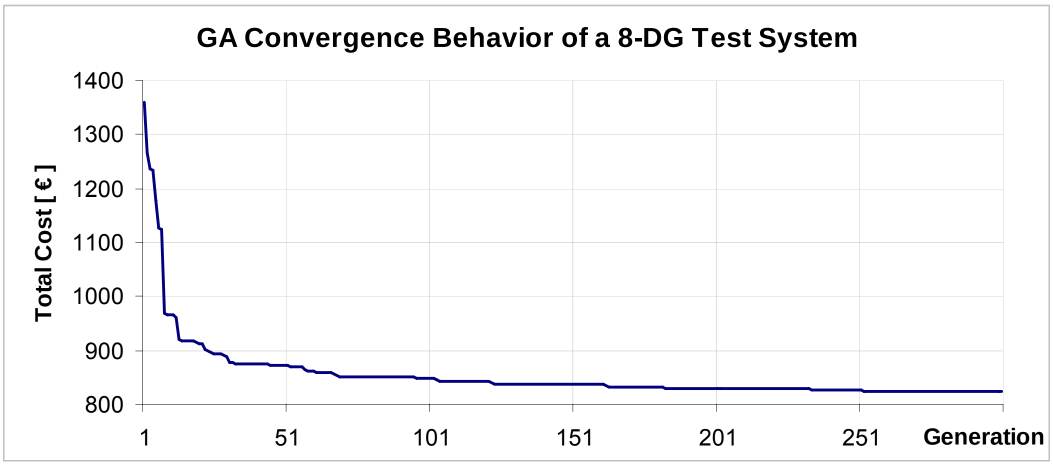


Figure 6-9 Sample GA Convergence Behaviour

7 Summary of Evaluation Results

7.1 Evaluation Results under Standard Test Conditions

7.1.1 Balancing and Energy Results

In Figure 7-1 and Figure 7-2, the load-side and MS-side self supply levels are shown for different countries and different Microgrid setups under Standard Test Conditions (STC). The load-side self supply level refers to the ratio of MS-supplied load demand over accumulated annual consumption figure, while MS-side self supply level refers to the ratio of MS-generated electricity that is consumed by local load in percentage of total generation.

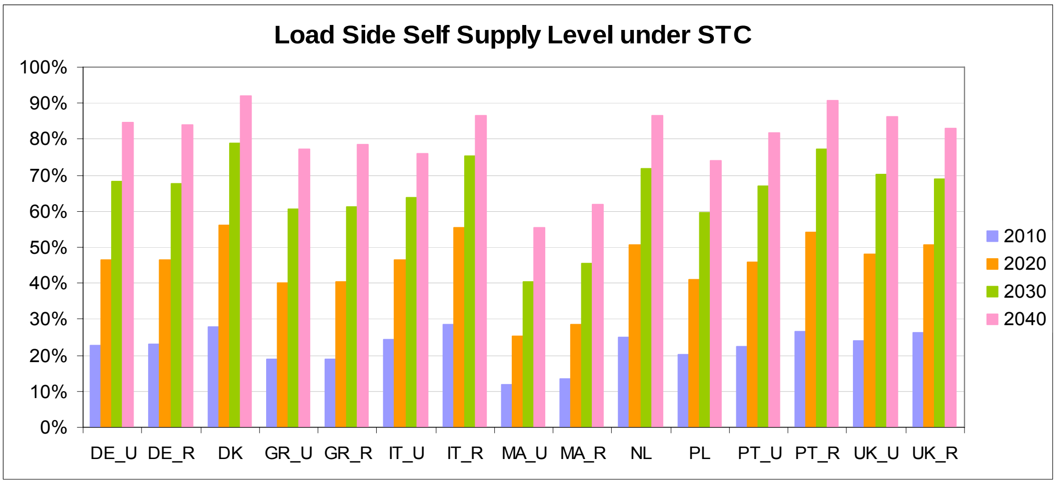


Figure 7-1 Microgrid Self Supply Level on Demand Side, STC Condition

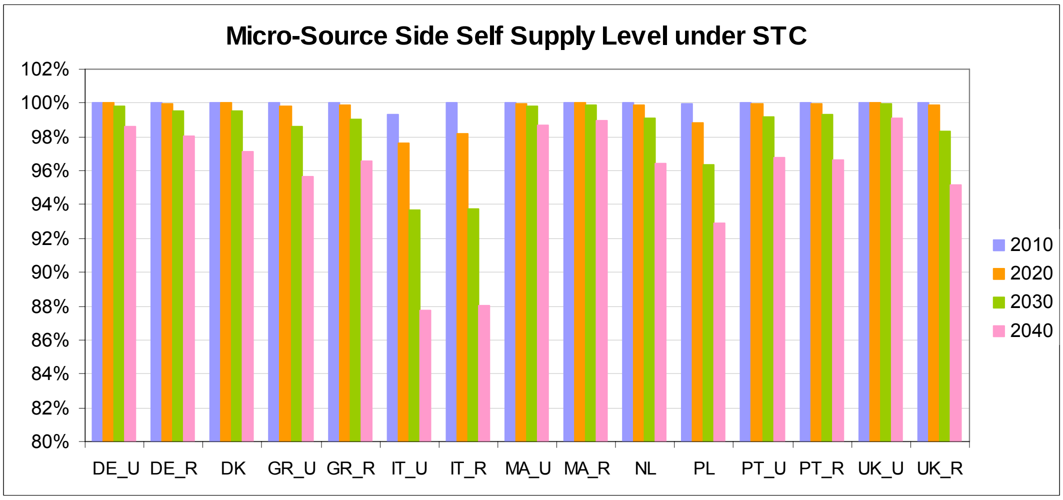


Figure 7-2 Microgrid Self Supply Level on Supply Side, STC Condition

Figure 7-1 shows that most Microgrids started with 15% to 25% self sufficiency level in 2010 and could eventually supply 70% to 90% (for most grids) of local demand by 2040. The main exception here is Macedonia, which starts from 10% to 15% in 2010 and ended up with around 60% self sufficiency in 2040 — this can be mainly explained by the lower wholesale and retail price levels assumed for Macedonia, which might potentially lead to low MS utilisation rate (further shown by Figure 7-3) and low self sufficiency level in consequence.

Figure 7-2, on the other hand, clearly suggests that even with high MS penetration levels (up to the case of 2040), default price setting with retail and wholesale price gap will lead MS units to supply locally at most of the time. A general local supply ratio of >95% can be observed with main exception of Italy, where high electricity prices tend to encourage MS units export more often than average level seen from other countries.

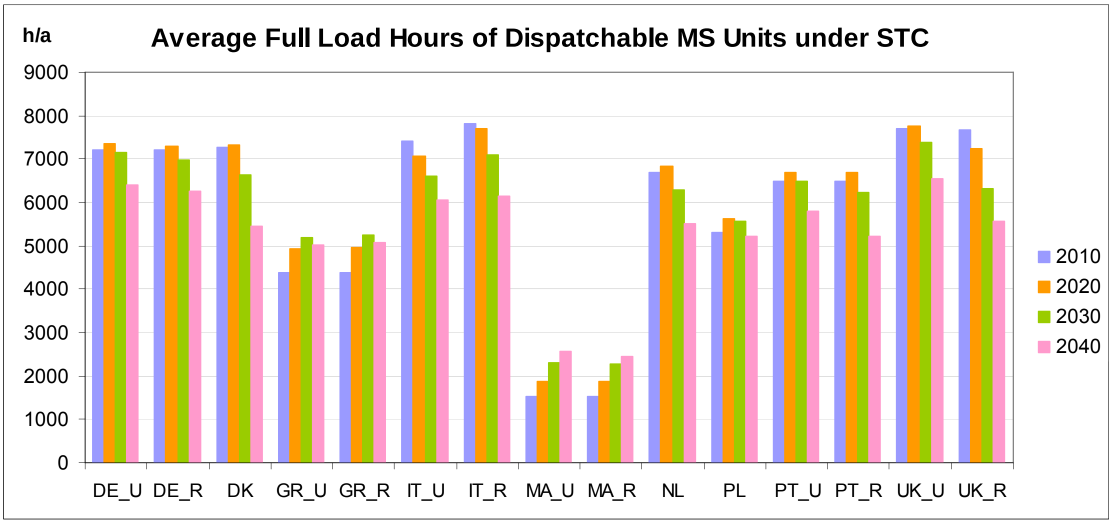


Figure 7-3 Full Load Hours of Dispatchable MS Units, Standard Test Condition

In Figure 7-3, the full load hours of dispatchable MS units are listed for the STC cases. It is quite interesting to observe that countries with high initial FLH data in 2010 (>6000 h/a) are generally experiencing reduction of FLH value as time progresses to 2040; while countries started with low FLH value (i.e. Greece and Macedonia) have increasing FLH value with time advancement. Specifically, the extremely low FLH hours (<3000 h/a) of Macedonia fully explains its low self sufficiency level shown in Figure 7-1.

In Figure 7-4, estimated average per-kWh premium support levels (on top of Microgrid price) are shown for ensuring profitability of subsidized RES units. The high initial values of Italy and Portugal can be mainly explained by high PV penetration levels estimated for both countries.

In general, Figure 7-4 shows that the majority of countries are able to withdraw from financial supports for RES units within a Microgrid by 2030 or 2040, as the internal trading prices are already sufficient for maintaining general unit profitability without external intervention. Slow introduction of RES units to Microgrid internal market can be explained either by adopted MS technology (e.g. PV for Portugal) or low electricity price in general (case of Macedonia).

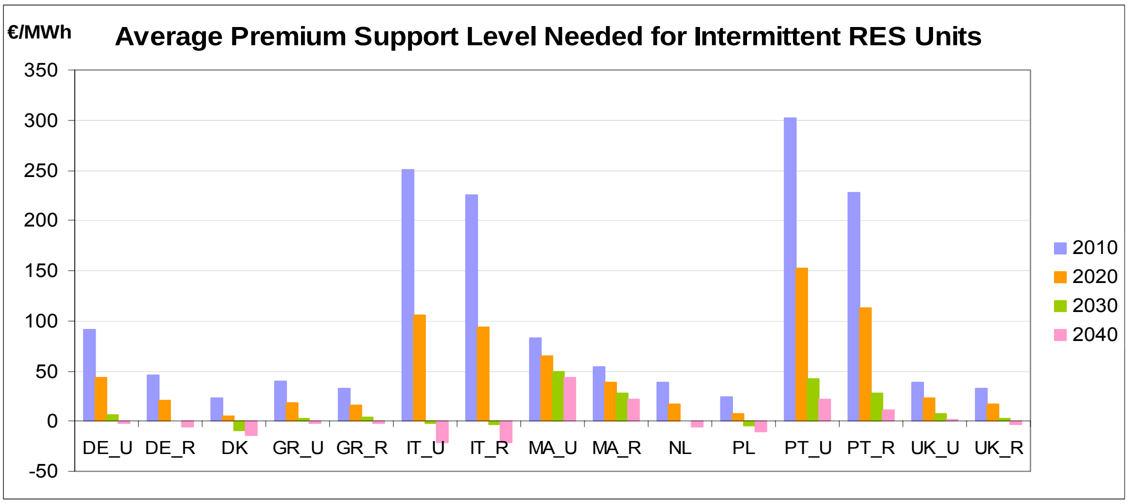


Figure 7-4 Needed Premium Support Level for RES Units, STC

7.1.2 Technical Benefits

Figure 7-5 shows the potential loss reduction credit for the part of LV network within a Microgrid. The figures correspond to the ideal situation with optimal allocation of MS units. A good correspondence of loss reduction credit and the (load-side) self sufficiency level (Figure 7-1) can be observed, which means Microgrids with optimally allocated MS units could avoid a significant amount of internal energy loss when the majority of load demand can be met locally by MS units.

However, in reality a Microgrid operator might only hold a limited impact on the dimensioning and allocation of MS units, which means the projected loss reduction credits shown in Figure 7-5 may fail to be realized in full extent—in some extreme cases, interconnection of disproportionally large MS units at weakly loaded network locations could even lead to increase of energy loss. Therefore one important task of Microgrid planner and regulator is to ensure efficient and effective MS interconnection schemes to maximize technical benefits from the Microgrid — this same principle applies also to the maximization of voltage and loading benefits.

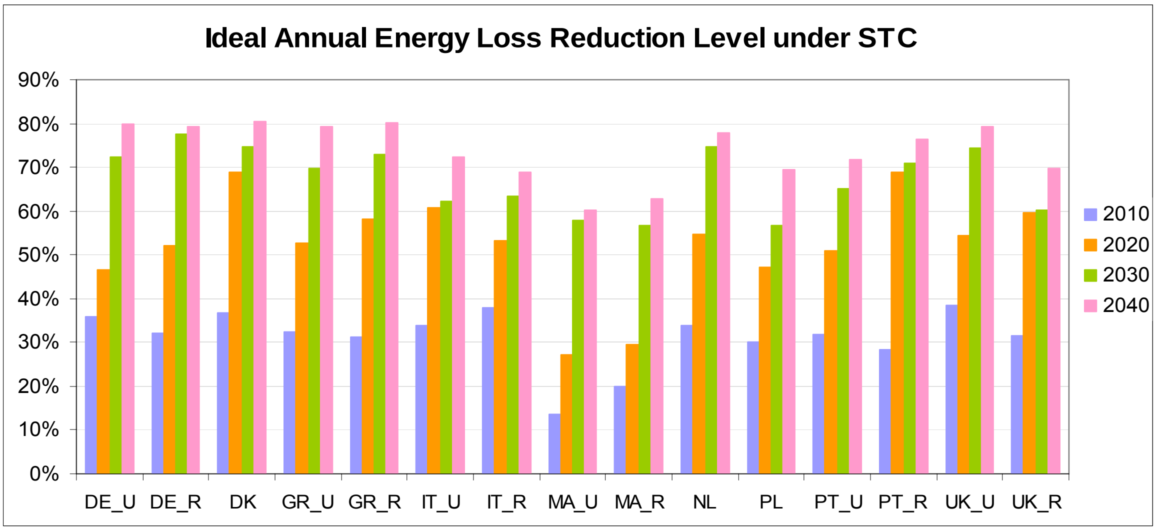


Figure 7-5 Annual Energy Loss Reduction Level (Ideal Network Condition), STC

In comparison with potential loss reduction credit, the estimated maximum voltage regulation credit from Microgrid is shown to be generally smaller in dimension (Figure 7-6).

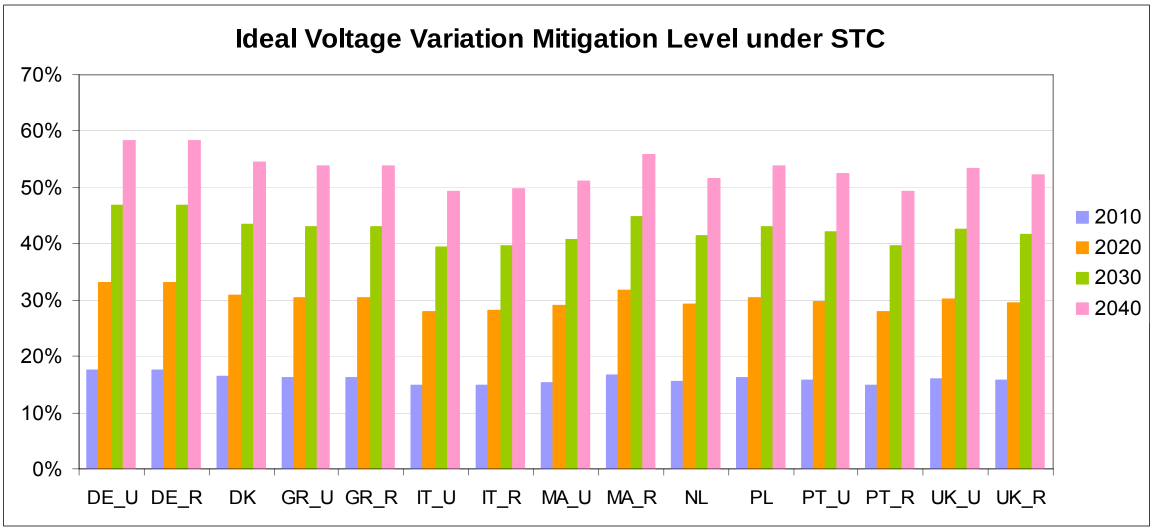


Figure 7-6 Ideal Voltage Regulation Credit, STC

The main reason behind is the non-controllability of active power output from intermittent RES units—as R/X ratios of distribution lines are generally quite high in tested grids, reactive power control from MS unit could only contribute approximately 10% to 30% of total voltage regulation power. Therefore, voltage controllability in tested Microgrids comes primarily from dispatchable MS units.

Similar to the case with voltage regulation, the peak reduction credit of Microgrid also depends heavily on the amount of dependable active power sources. In Figure 7-7, it can be seen that peak reduction level of all tested Microgrids almost relies entirely on the installed capacity of dispatchable MS units, as reactive power contribution to line currents are estimated to be even smaller in comparison with the case of voltage regulation.

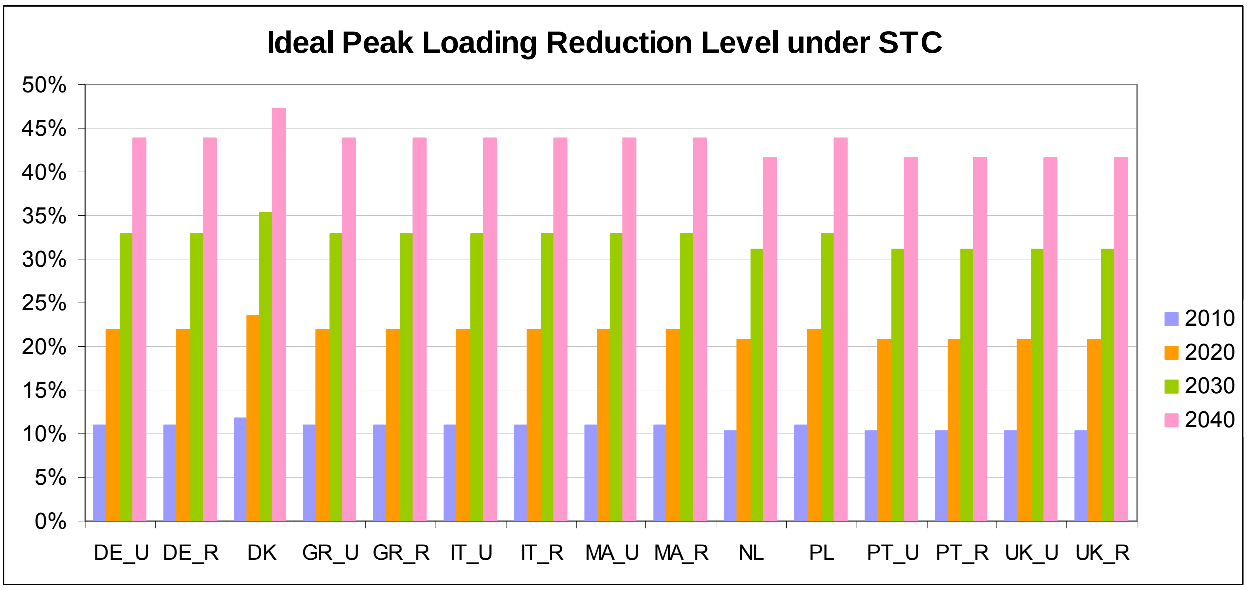


Figure 7-7 Ideal Peak Load Reduction Credit, STC

7.1.3 Environmental Benefits

In Figure 7-8 and Figure 7-9 demonstrate the environmental benefits of Microgrids in absolute and relative values.

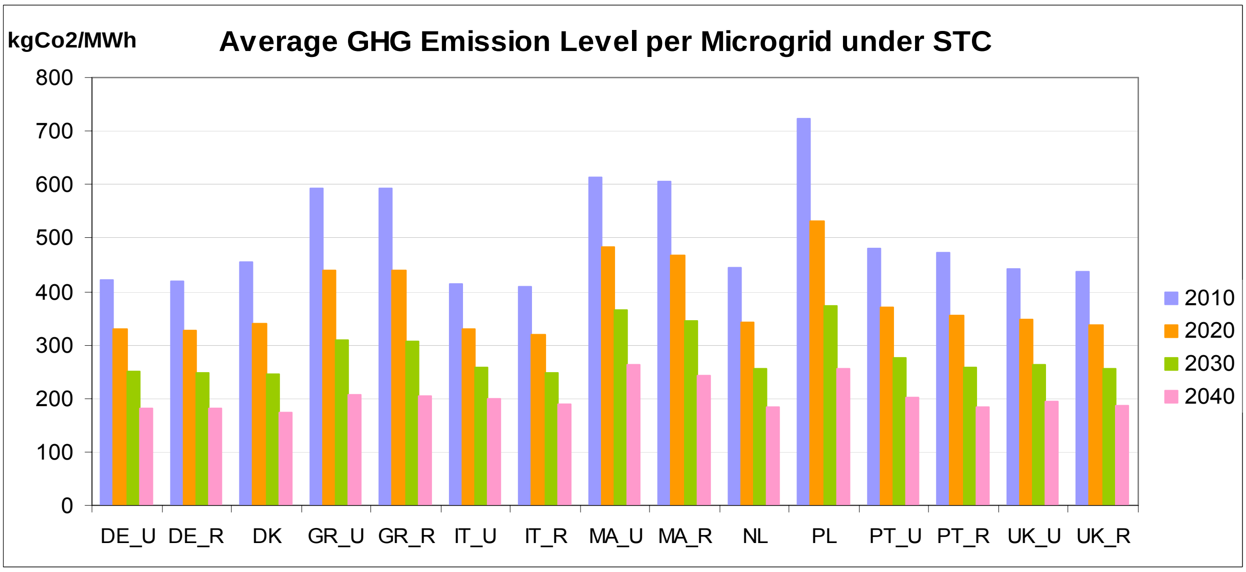


Figure 7-8 Average Microgrid GHG Emission Level, STC

Figure 7-8 has indicated a general convergence of Microgrid GHG emission level to around 200 kg (CO_2 equivalent)/MWh by 2040 despite very different starting points in 2010—this convergence can be explained by the high resemblance of load-side self sufficiency level in 2040, as shown by Figure 7-1.

In Figure 7-9, the GHG reduction credits of Microgrid are represented as percentage of original emission levels of each examined country. It is quite obvious that countries started with high emission levels could expect reduction credits as high as over 50% (e.g. Greece and Poland), while countries with lower initial emission (e.g. Italy) find comparatively smaller credits by 2040.

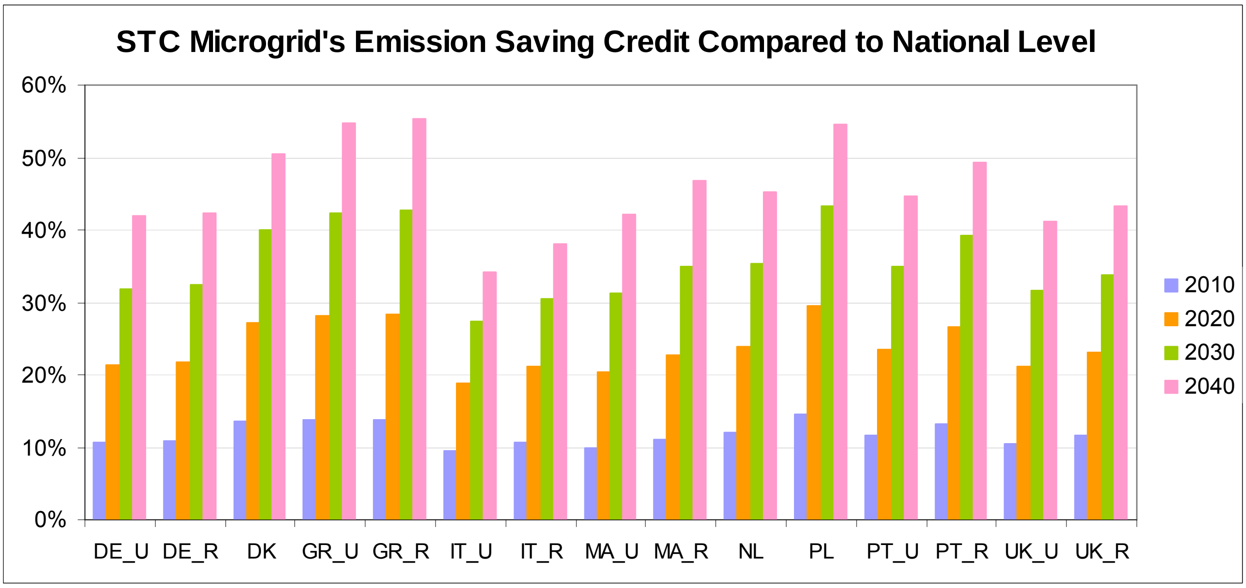
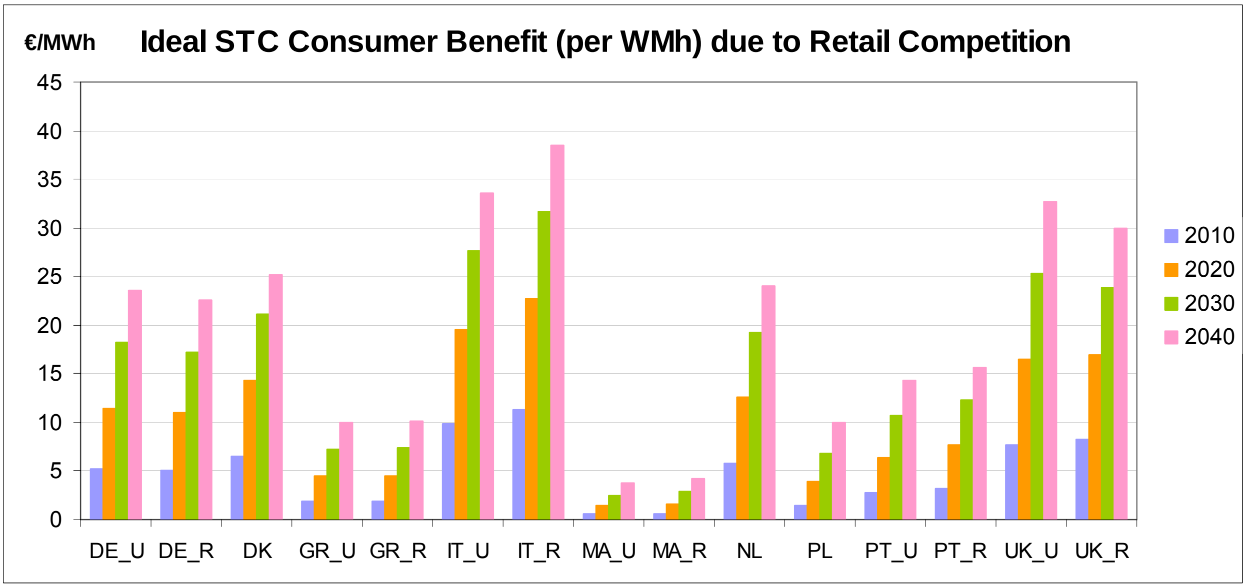


Figure 7-9 Average Microgrid Emission Saving Credit, STC

7.1.4 Economic Benefits: Consumer Side

In Figure 7-10, the potential economic benefit of market selectivity on consumer side is shown in both absolute (€/MWh) and relative (%) terms.



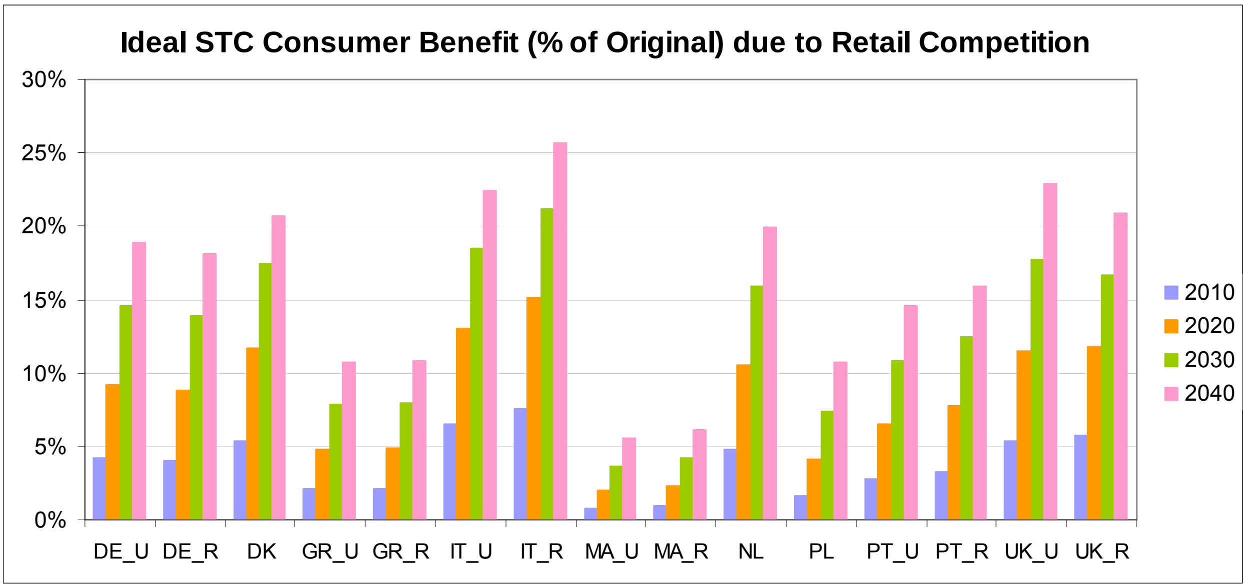


Figure 7-10 Ideal Consumer Benefit due to MS Selectivity, STC

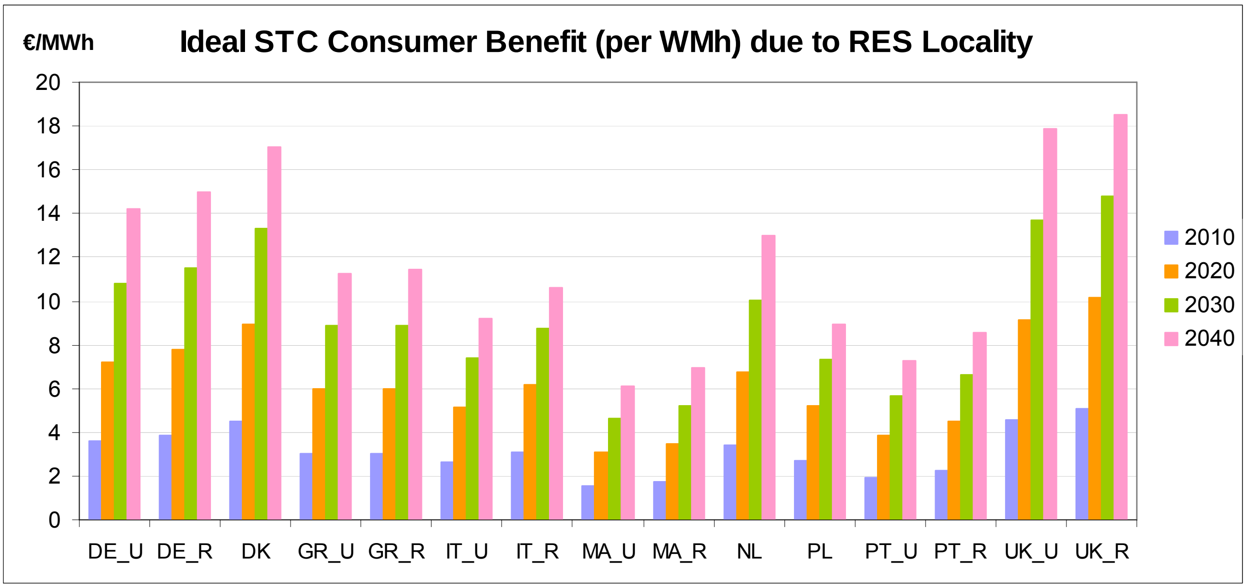
As already explained in section 5.4.1.1, this load-side selectivity index is based on the assumption that all unsubsidized MS units are operated under zero profit (e.g. when end consumers own the MS units) and DSO does not impose any grid charge upon internal energy consumption within a Microgrid. In addition, it should be noted that the relative price reductions are calculated in percentage of mean retail prices without tax.

The comparatively large national variations of load side selectivity benefits can be attributed to two factors: FLH values of dispatchable MS units and the profit margins between retail prices and MS costs. As essentially FLH values of MS units are also determined by market prices, load side selectivity benefit level can be seen as extremely sensitive to national electricity prices.

In Figure 7-11, the potential economic benefit due to RES locality value on consumer side is shown in both absolute (€/MWh) and relative (%) terms.

Unlike benefits identified from market selectivity, the RES locality value is totally dependent on regulatory support for physical realization—which means by default, no market forces will grant consumers with such benefits due to natural cash flows within a Microgrid. However, if a Microgrid consists completely of subsidized RES units, then consumers will not experience any selectivity benefit, and identification of RES locality value (avoided UoS charge) will become the only source of consumer-side motivation available at all.

As consumer side RES locality benefits are deduced partially from standard grid charges, the default use of system charges can be seen as the sole determinant of national variations in locality benefit value. Consequently, in comparison with variations as high as ten fold from the selectivity benefit indices, national locality benefit variations are topped at three fold difference.



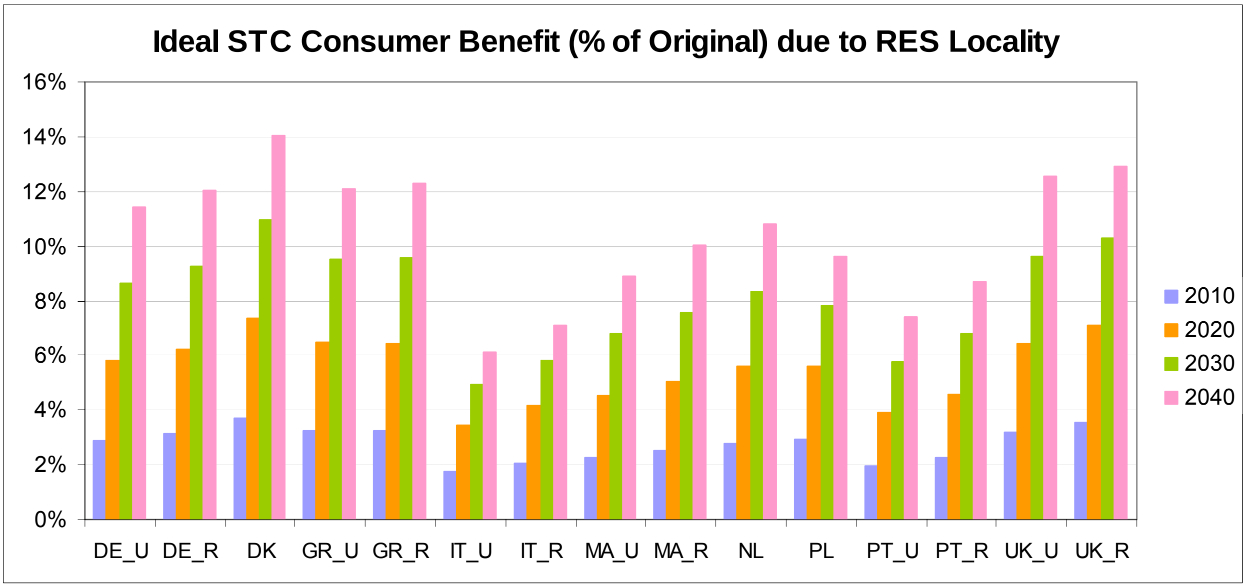
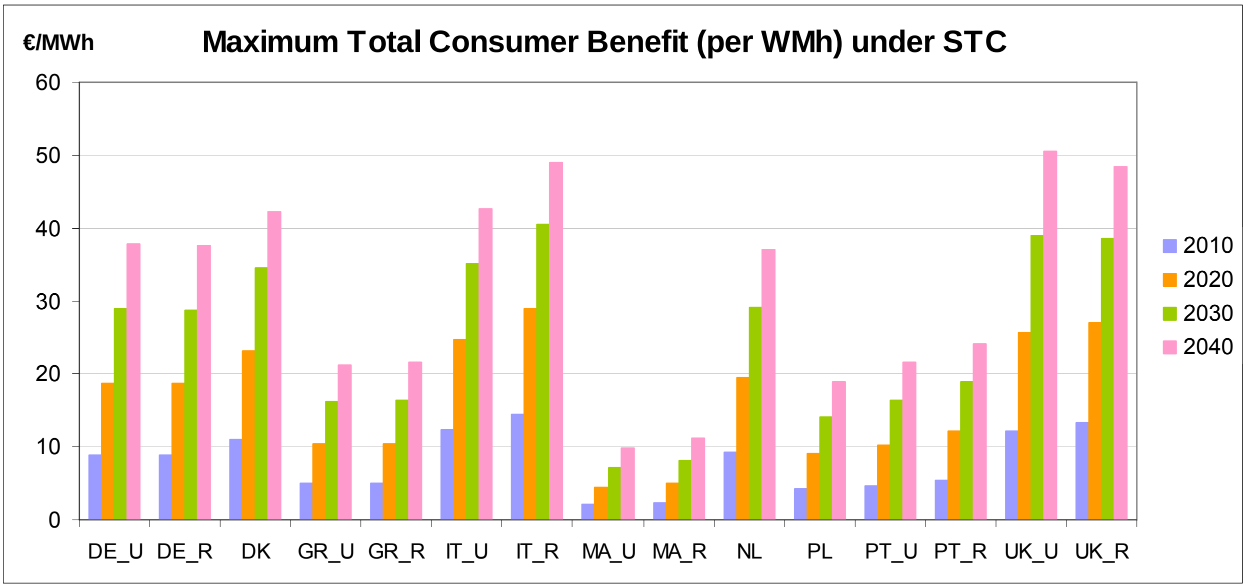


Figure 7-11 Ideal Consumer Benefit due to RES Locality, STC

In Figure 7-12, the maximum value of total economic benefit on consumer side is shown in both absolute (€/MWh) and relative (%) terms.

A large variety of cost saving potentials can be observed from Figure 7-12, ranging from 0.002 cent/kWh in 2010 to 0.05 cent/kWh in 2040. The majority of results, however, points to a cost saving range from 7% ± 5% in 2010 to 25% ± 10% in 2010—of course, if the cost saving ratios need to be represented for retail prices with tax included, then national figures will be reduced by a variety of levels ranging from 4% to over 50%.

In the end, it should be again noted here, that the benefit values shown in Figure 7-12 are based on complete transfer of selectivity benefit to consumer side as well as regulatory support for partial grid charge exemption for local consumption of subsidized RES energy. If a Microgrid operator does not see consumers as a proper interest holder, then end consumers might have none of the benefits listed here and have to pay the same electricity prices as the original condition without Microgrid.



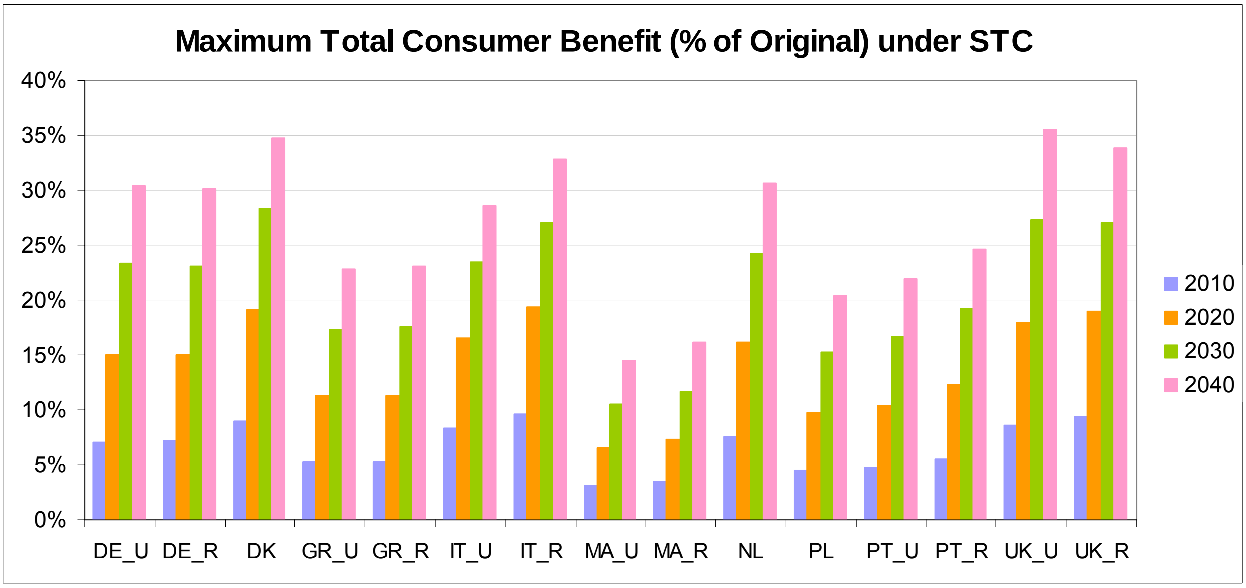


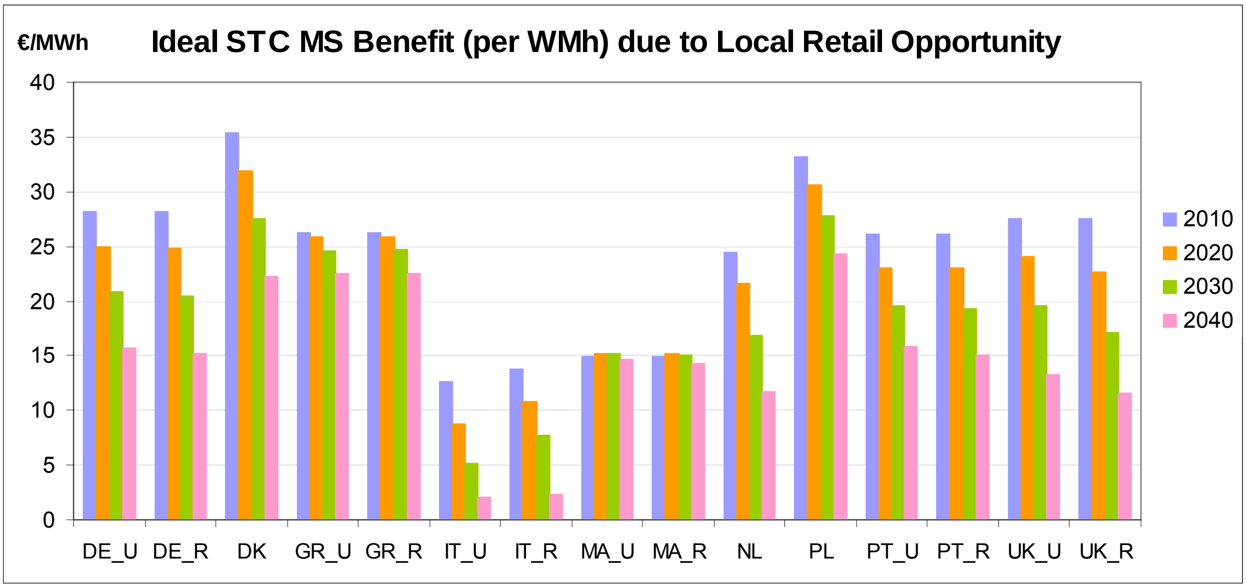
Figure 7-12 Ideal Total Consumer Benefit, STC

7.1.5 Economic Benefits: MS Side

In Figure 7-13, the ideal locality benefit on dispatchable MS side is shown in both absolute (€/MWh) and relative (%) terms.

As MS locality benefit is defined simply as the difference between MS cost and wholesale price level, it is actually an indication of opportune operation loss if the MS units are forced to sell to wholesale market instead of local consumers. As all values in Figure 7-13 are shown to be positive, it is quite obvious that none of tested Microgrid scenarios under mid-level price and real-time pricing setting could lead to direct MS profit (i.e. selling directly to wholesale market).

One obvious trend from Figure 7-13 is the gradual reduction of MS-side locality benefit with passage of time—this is basically in line with the cost reductions assumptions made in Figure 5-14. Later in the sensitivity analysis section, increase of market price to high-level setting will be revealed to have similar impacts in terms of reducing the opportune loss of MS locality.



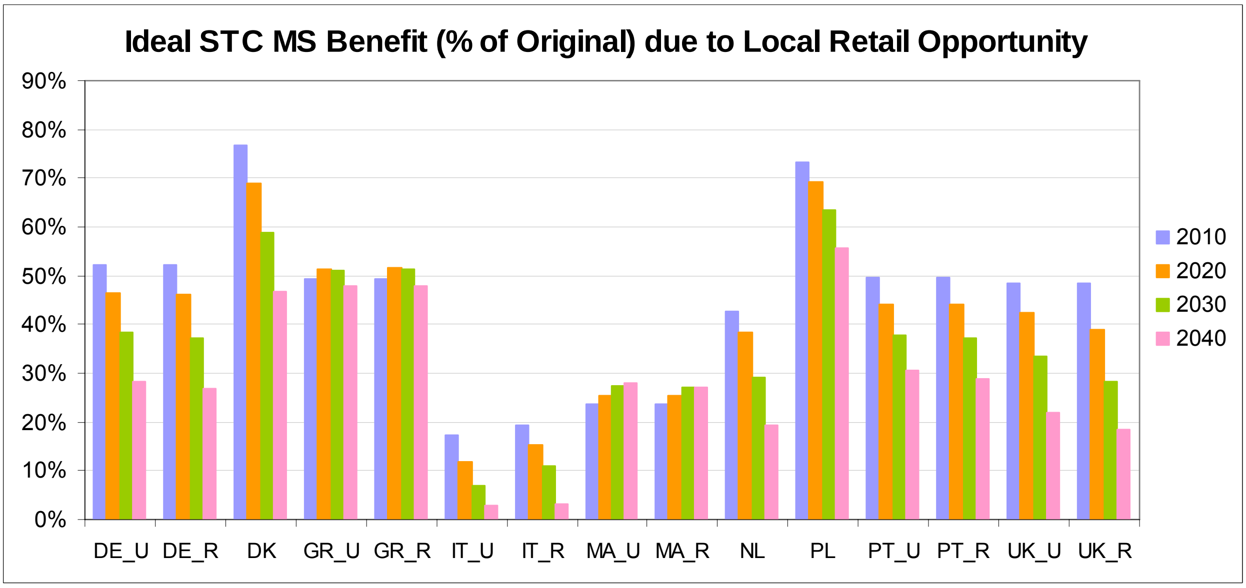
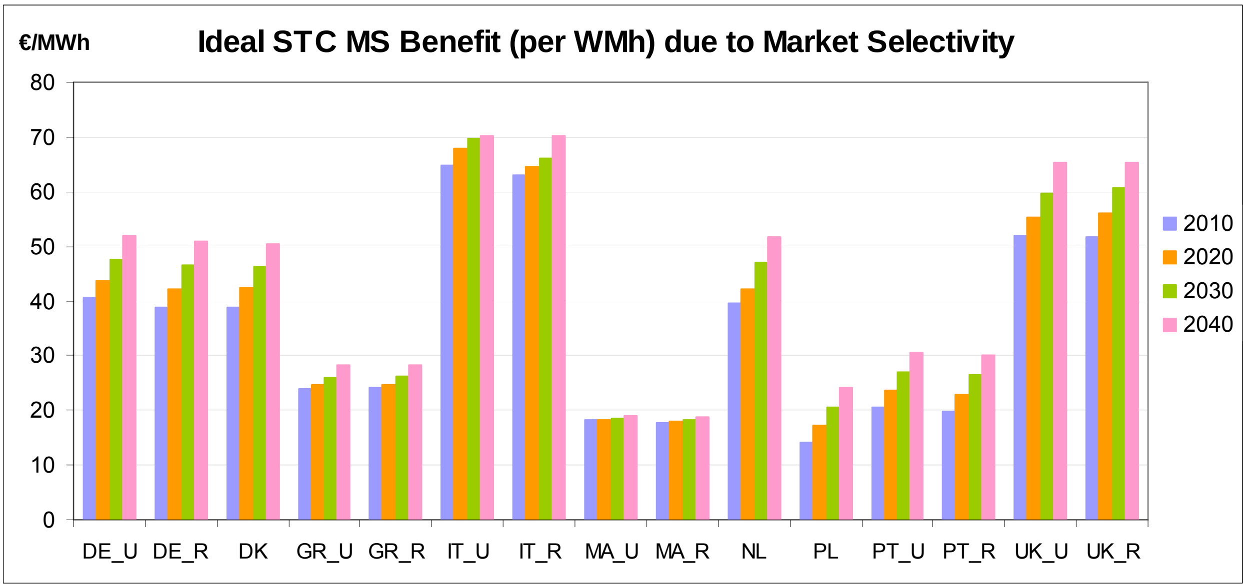


Figure 7-13 Ideal MS Benefit due to Locality Value, STC

In Figure 7-14, the ideal selectivity benefit on dispatchable MS side is shown in both absolute (€/MWh) and relative (%) terms.

As already explained in section 5.4.1.2, the selectivity value on MS side is actually referred to the same benefit used for load-side selectivity value—the difference between both terms only lies in the divided total amount of energy consumption (load side) or generation (MS side). As a consequence, to reach the full extent of selectivity benefit listed in Figure 7-14, consumers are expected to pay the same tariff before Microgrid implementation and DSO are not expected to collect any energy-specific grid charge upon locally consumed MS energy.

In comparison with locality value, the selectivity benefit is a much more important index for MS units as it can also be seen as the maximum achievable profit margin for the units. The results from Figure 7-14 suggest a very close correlation between MS profitability and retail market price level, which yields high profits at 60-70 €/MWh for high-price countries (e.g. Italy and UK) and much lower results around 20 €/MWh for low-price countries (e.g. Greece and Macedonia)



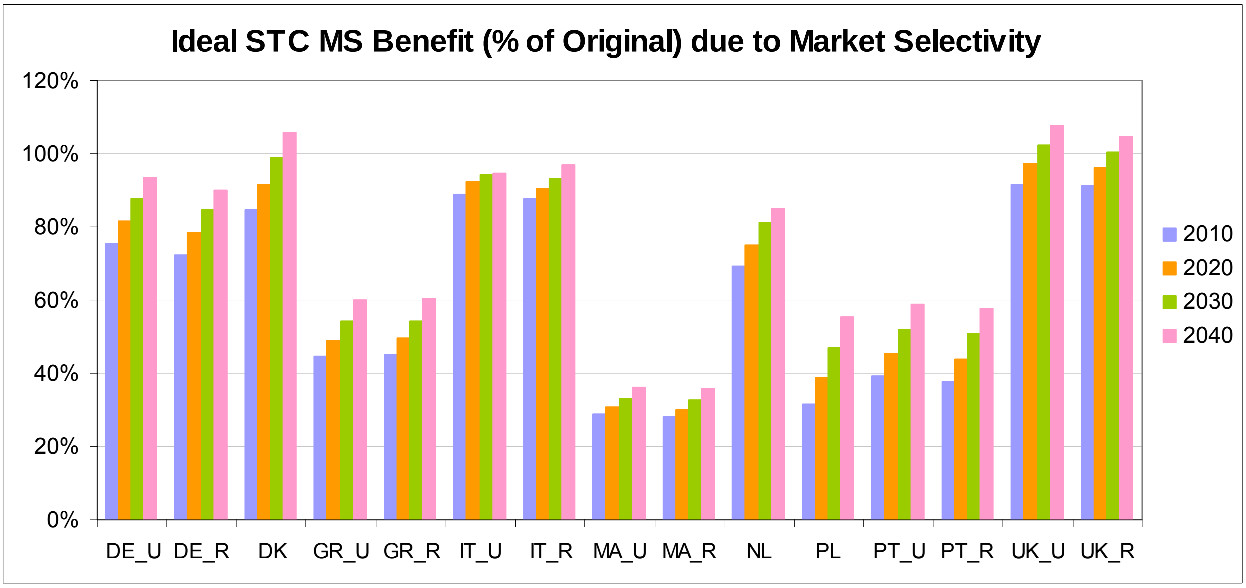
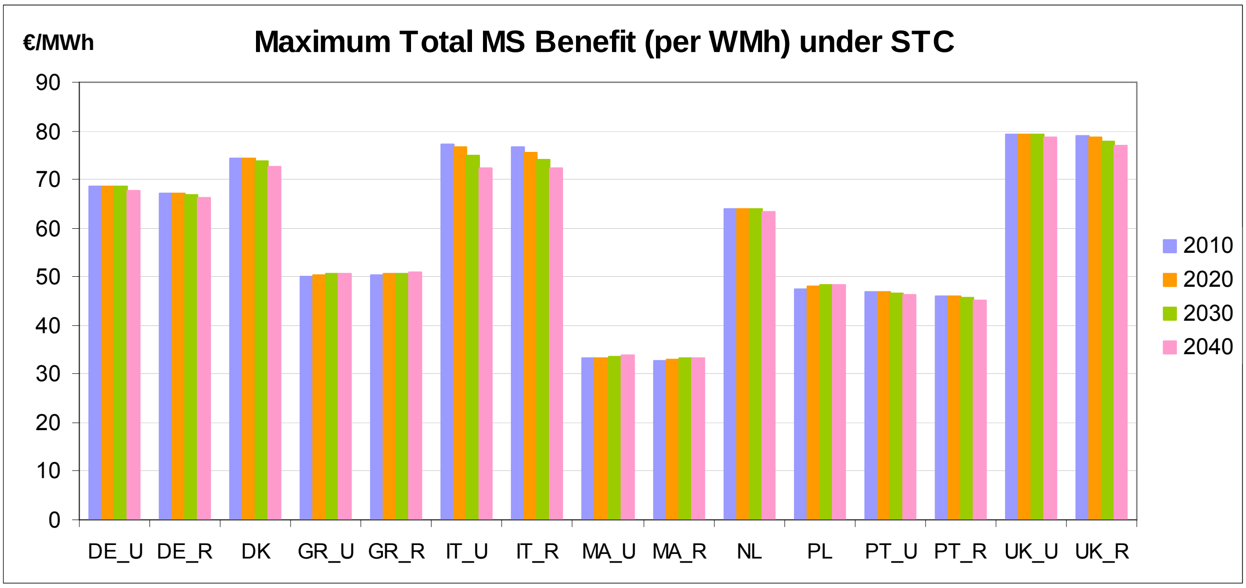


Figure 7-14 Ideal MS Benefit due to Market Selectivity, STC

Figure 7-15 shows the maximum total benefit on dispatchable MS side in both, absolute (€/MWh) and relative (%) terms.

Similar to the total benefit definition on load side, the MS side benefit is also summed from locality benefit value and selectivity benefit value. The difference between these two indices lies in the fact that locality part of MS benefit is not subject to any restriction and can be seen as the bottom line of total MS benefit (as long as a MS unit is working), whereas total consumer benefit could easily drop down to zero under adverse environments.

An obvious observation from Figure 7-15 is the fact that variations in MS cost from 2010 to 2040 basically have negligible impacts on total benefit levels of all examined countries—this can be explained by viewing maximum total MS benefit simply as the difference between average retail and wholesale prices in an examined country, which stays largely constant despite MS cost variation and market price changes (to be discussed further in sensitivity analysis).



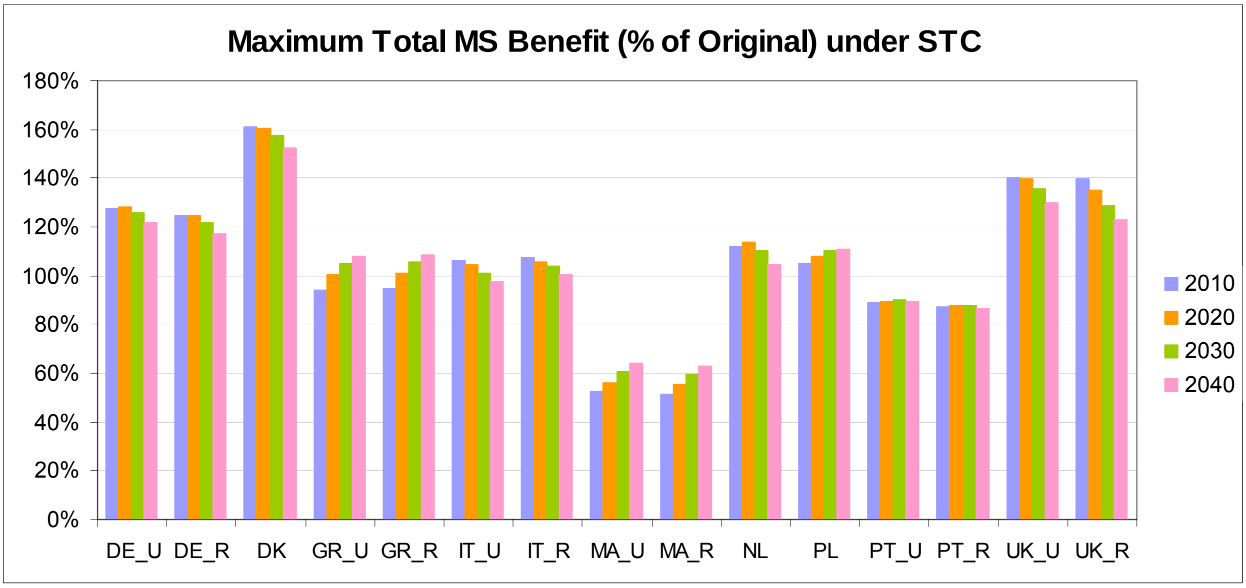


Figure 7-15 Ideal Total MS Benefit (Maximum), STC

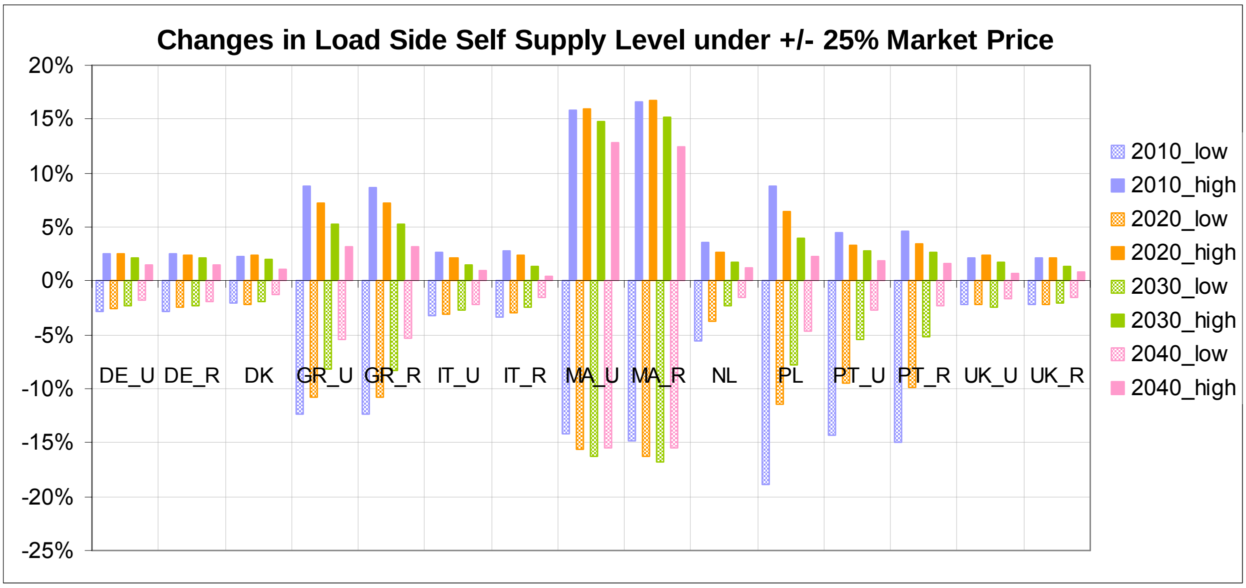
7.2 Sensitivity Analysis of Market Price and Pricing Policy Variations

7.2.1 Balancing and Energy Results

Potential changes induced by market price variations and pricing policy differences on load side self supply level can be seen from Figure 7-16.

Firstly, it can be clearly seen that reduction of market price invariably leads to reduction of MS usage and reduction of Microgrid self sufficiency level, while the exact opposite can be said for increased market price level. A notable fact is that low- to mid-price countries (such as Greece, Macedonia, Poland, and Portugal) are much more sensitive to annual wholesale price level (up to ± 15%) in comparison with high-price countries (largely below ± 5%).

Interesting, in comparison with real time price setting, application of constant pricing scheme has negligible impact on high-price countries but visibly increases self sufficiency level of low- to mid-price countries. Uniform pricing, however, always leads to lowest self sufficiency levels.



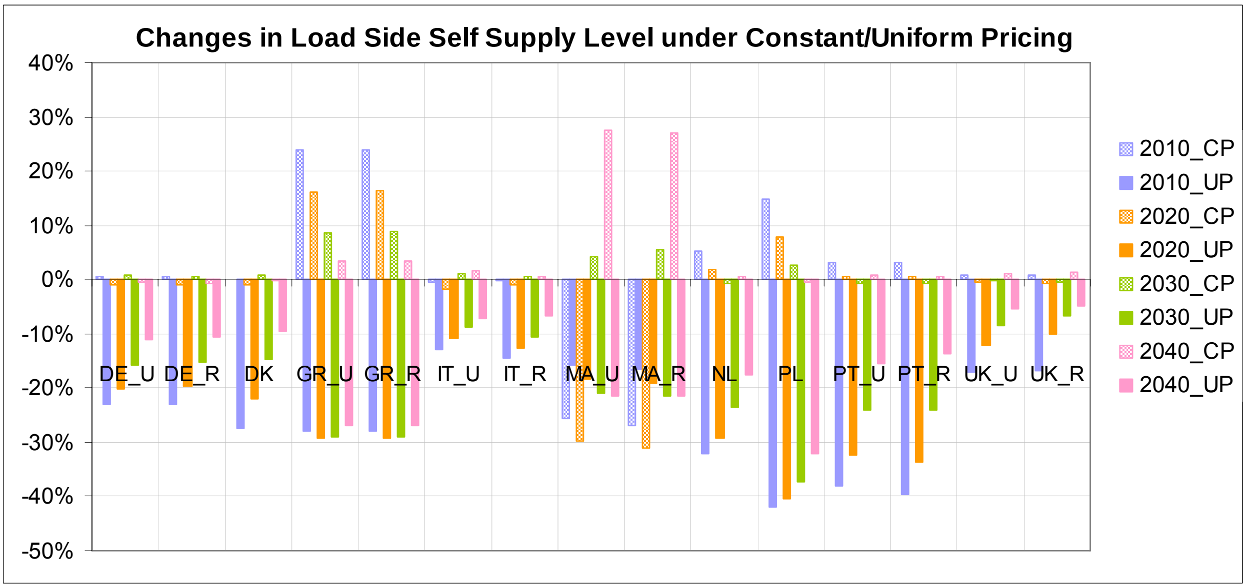
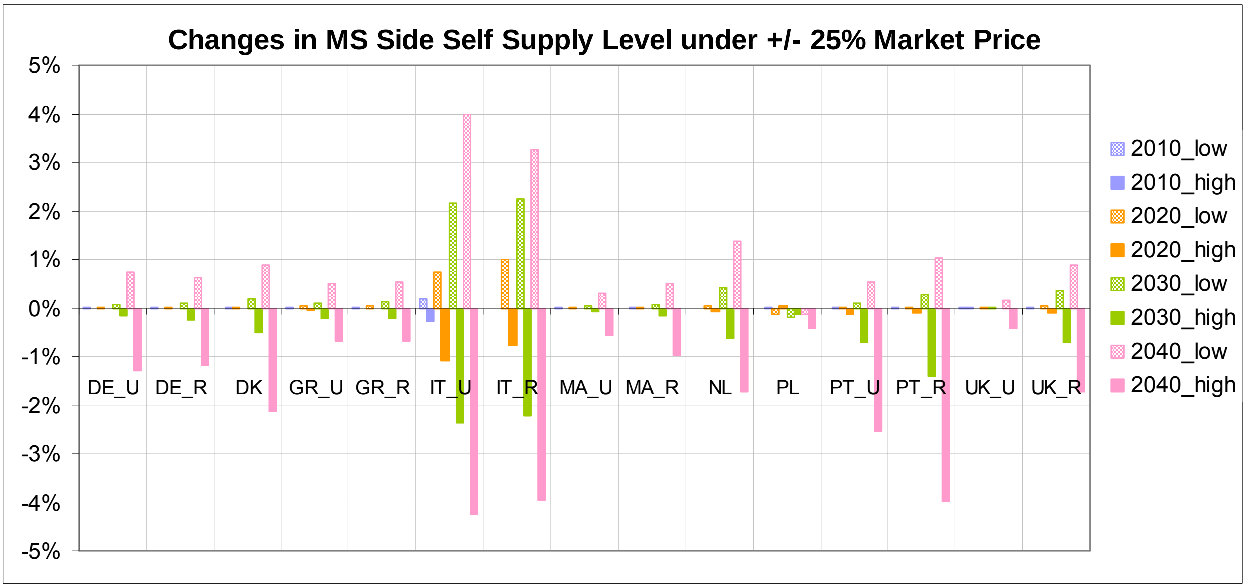


Figure 7-16 Market Price and Pricing Policy Impact on Load Side Self Supply Level

Potential changes induced by market price variations and pricing policy differences on MS side self supply level can be seen from Figure 7-17.

In contrast to the load-side case, MS side self supply level increases with lower market prices and decreases as average market price goes up—which can be easily explained by the potential elimination or creation of export opportunities during peak price hours. Although a number of countries reach MS self supply level variation of ± 4%, the majority of data falls within ± 1%, which indicates a very small impact of market price on MS export opportunities—this suggests that export chances in even a quasi-islanded Microgrid (2040 case) will be mainly determined by load level instead of general price level.

Examination of consequences due to constant pricing scheme reveals similar results as market price level impact, where variations are generally within ± 2% can be largely discarded. Uniform pricing scheme, however, could induce reduction of MS self supply ratio (thus increasing export level) by 10% to 15% in 2030 and 2040 scenarios.



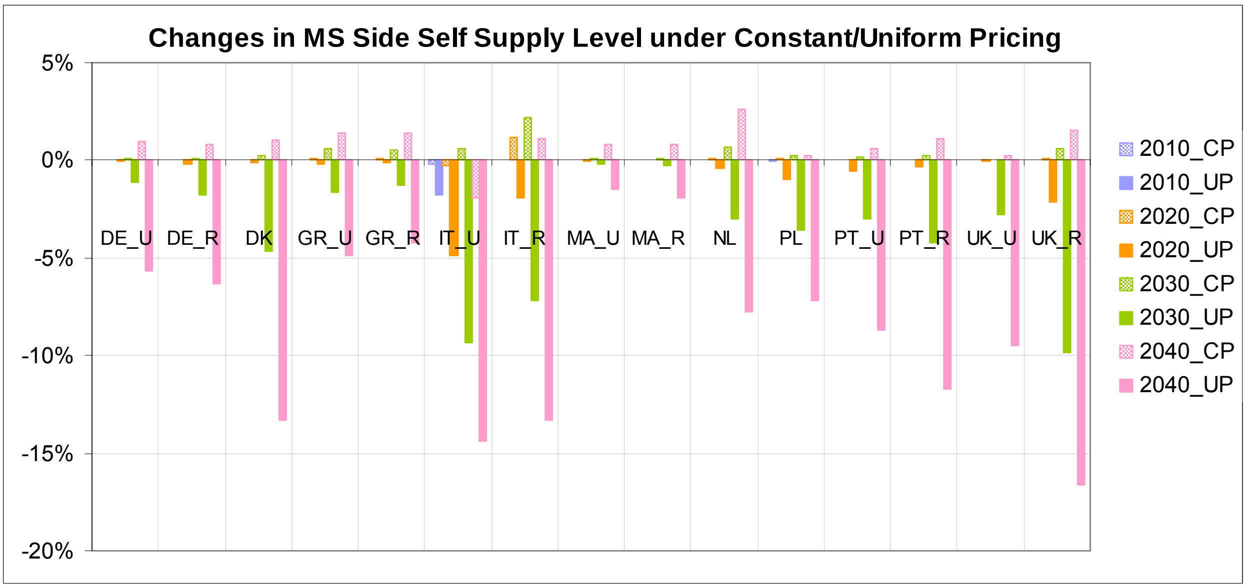
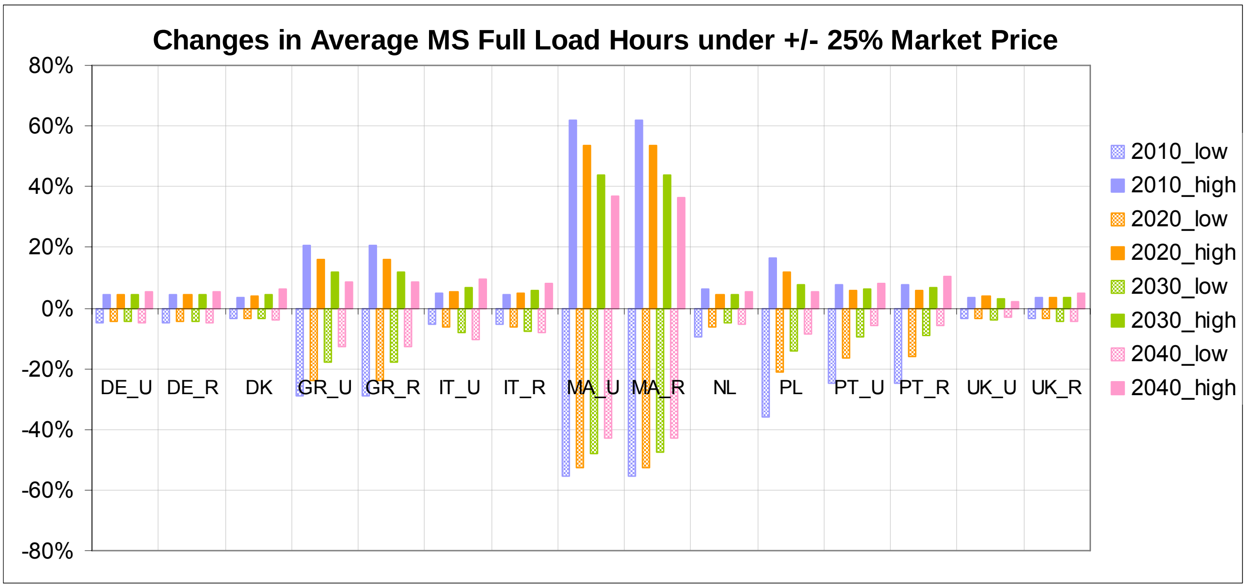


Figure 7-17 Market Price and Pricing Policy Impact on MS Side Self Supply Level

Potential changes induced by market price variations and pricing policy differences on mean FLH of MS units can be seen from Figure 7-18.

The impact of market price variation on MS FLH value shows a very similar trend as load side self supply level given by Figure 7-16. However, the FLH values of low-price countries exhibit an even higher level of sensitivity to average wholesale price variations (up to ± 60% in the case of Macedonia). High-price countries (e.g. Germany, Denmark, Italy, Netherland, and UK) generally experience variations below ± 10% and are hardly impacted by wholesale market price level.

Constant pricing, though having negligible impacts on high-price countries, is found to invoke as high as 80% of FLH increase (compared to real time pricing) for low-price countries such as Macedonia, Greece, and Poland—which can be mainly understood as the benefit of price stability in adverse market setting. Uniform pricing poses a 20% to 80% FLH reduction level in 2010, which is decreased drastically with the passage of time—by 2040 some countries even start to experience FLH increase due to uniform pricing setting.



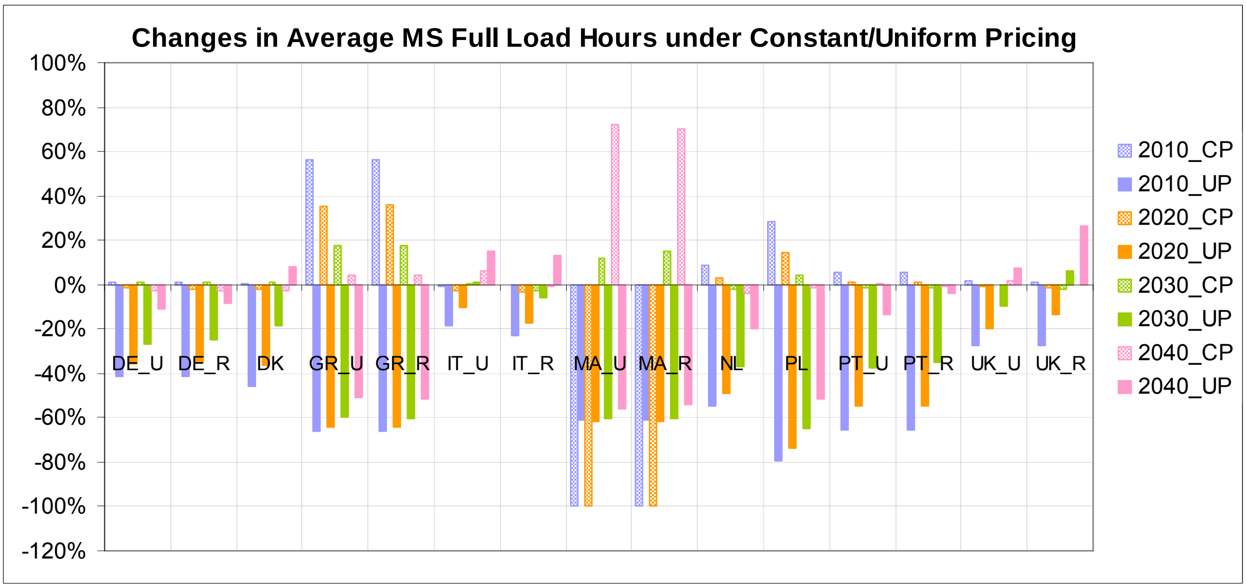


Figure 7-18 Market Price and Pricing Policy Impact on MS Full Load Hours

Potential changes induced by market price variations and pricing policy differences on required premium support level for RES units can be seen from Figure 7-19.

As already disclosed in section 7.1.1, the support levels shown in Figure 7-19 are calculated as the difference between mean RES production cost and average retail price level. Due to this linear correlation between market price and RES support requirement, variations in average wholesale price level induces proportional changes in RES support demands—i.e. higher prices leads to reduction of support demand and lower prices call for higher supports. In general, a 10% to 20% variation can be observed from ± 25% market price level change.

Application of constant pricing scheme induces increase of premium support requirement for some countries (e.g. DE, IT, NL, and PT) and poses lower support demands for the others (e.g. DK and UK). Uniform pricing, on the other hand, is assumed not to interfere with RES support schemes and consequently holds no impact over required national support levels.

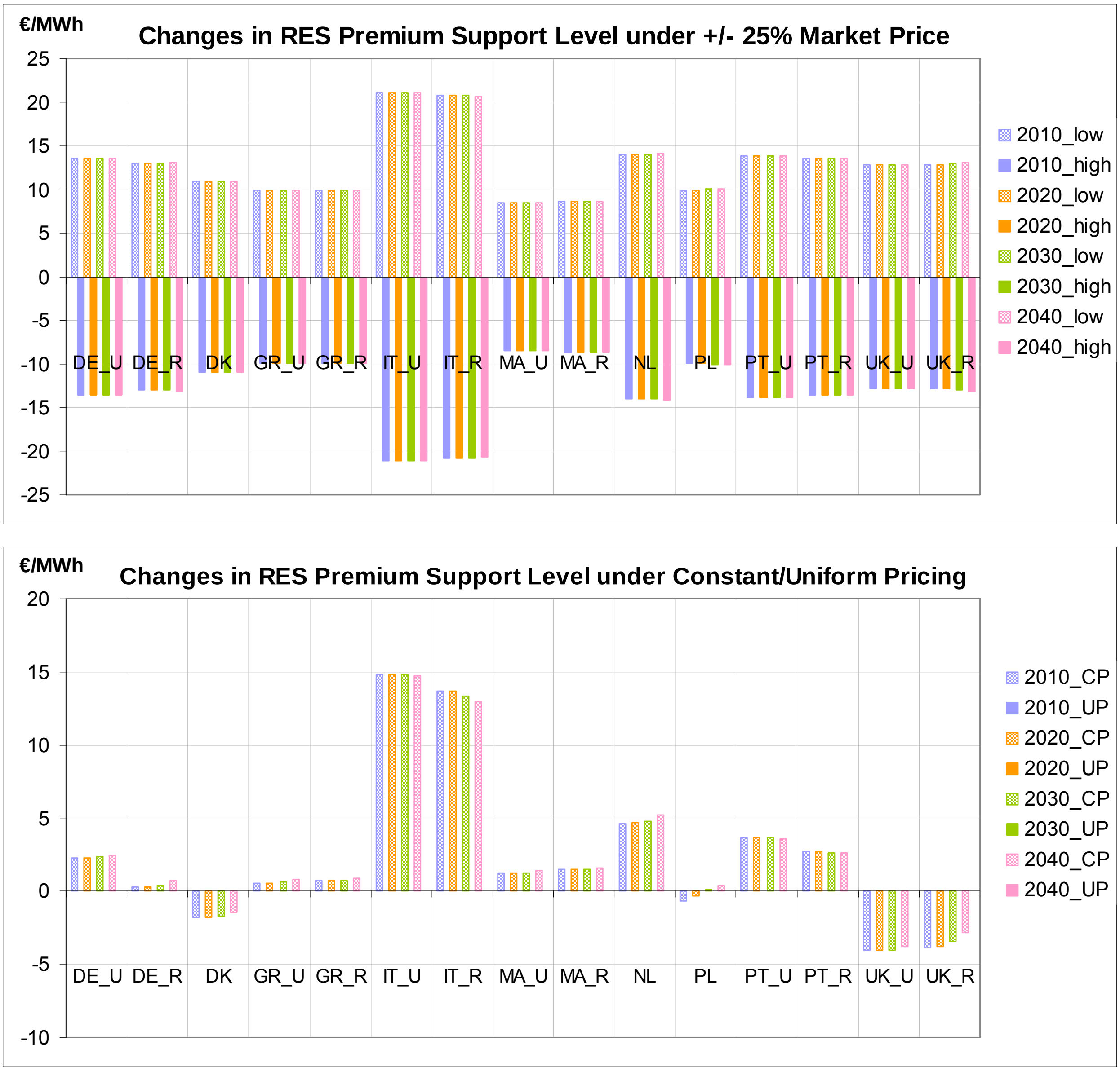


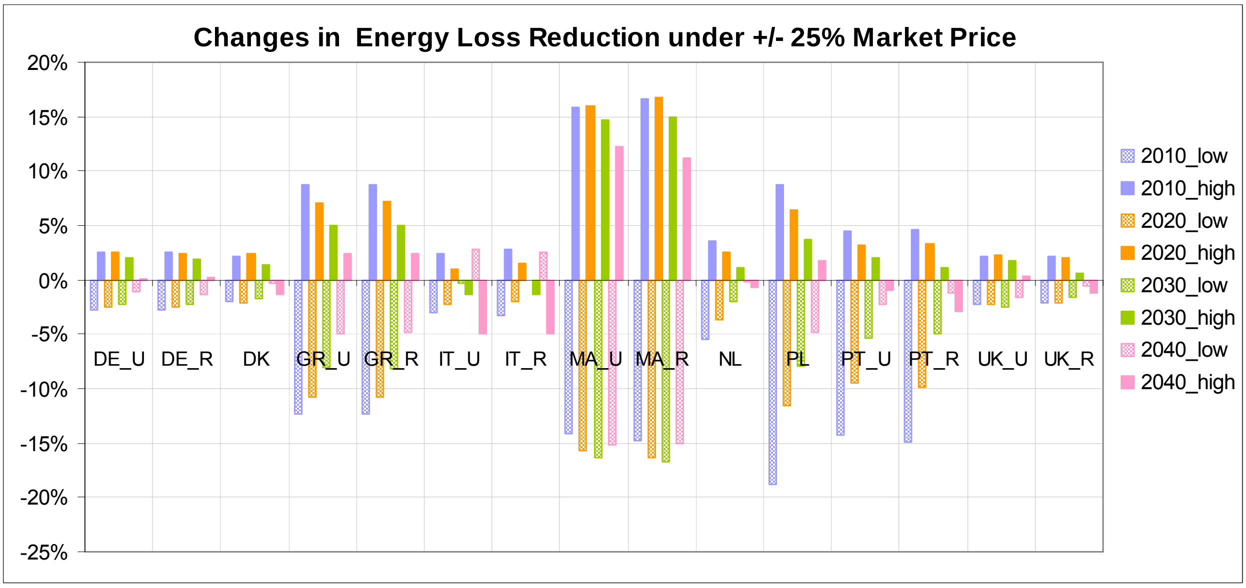
Figure 7-19 Market Price and Pricing Policy Impact on RES Premium Support Level

7.2.2 Technical Benefits

As voltage regulation and peak reduction credits are determined by instantaneous, extreme network conditions rather than summarized annual power flow results, both of them can be seem as independent from market price and pricing scheme impacts. Therefore, only the potential changes of Microgrid loss reduction credit is reviewed here in Figure 7-20.

Impact analysis of both market price variation and pricing scheme changes lead to similar trends as shown by load side self sufficiency level from Figure 7-16—this is of course caused by the comparatively low levels of MS export ratio for basically all examined simulation cases.

The conspicuous impacts of external Microgrid market setting upon its technical performance (in terms of loss reduction here) suggests that economic and technical aspects of Microgrid operation are deeply intertwined with a high degree of mutual interactions.



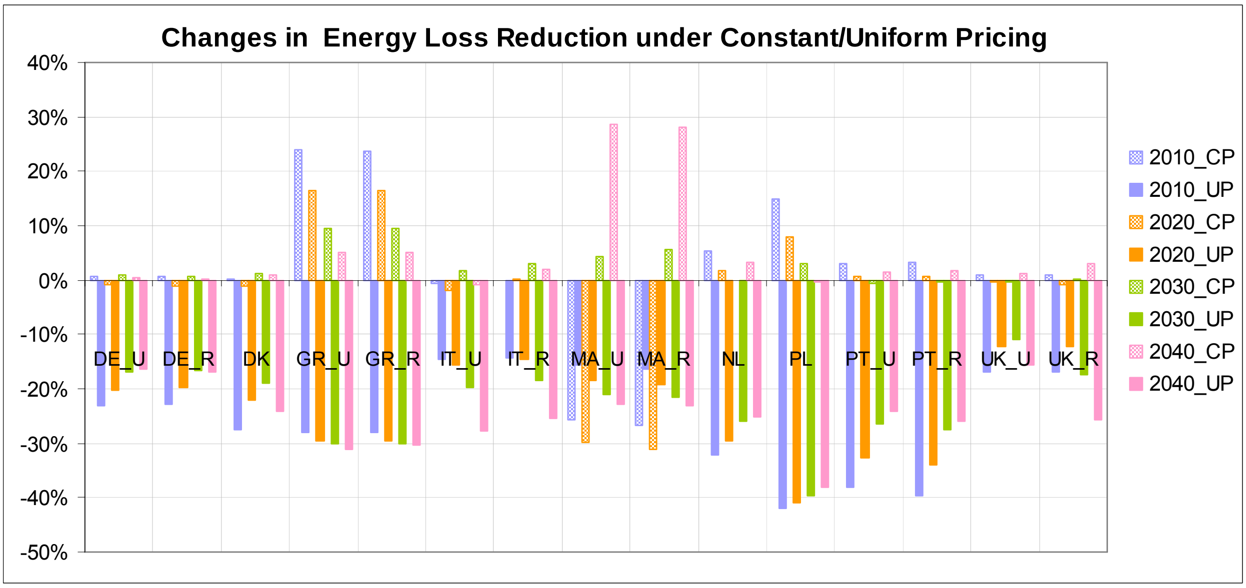


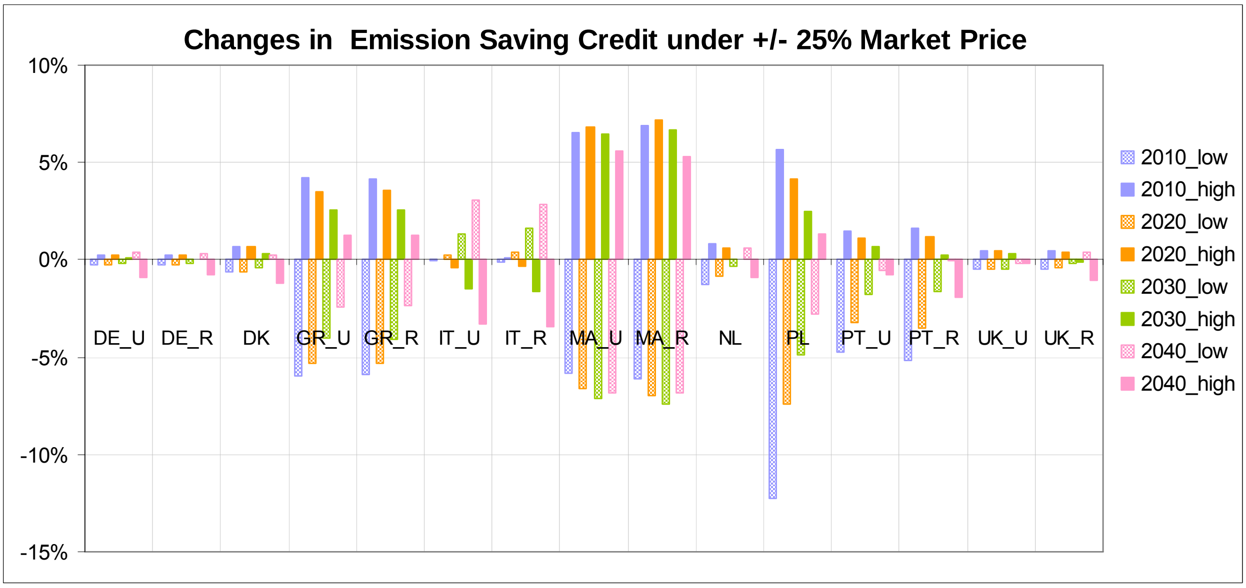
Figure 7-20 Market Price and Pricing Policy Impact on Loss Reduction Credit

7.2.3 Environmental Benefits

Potential changes induced by market price variations and pricing policy differences on Microgrid emission saving credits can be seen from Figure 7-21.

Comparison with Figure 7-16 again points to a very close correlation between Microgrid self sufficiency level and its emission reduction credit—of course, due to different starting points in terms of national emission level, the degree of emission sensitivities to market price or pricing policy variations are somehow even higher than the technical benefit (loss) case.

Despite large national variations in response to external pricing level and pricing setting, the actual impact of both criteria are comparatively small (< ± 10%) except for the uniform pricing case, which could potentially lead to a reduction of more than 25% in terms of GHG saving credit (compared to real time pricing condition).



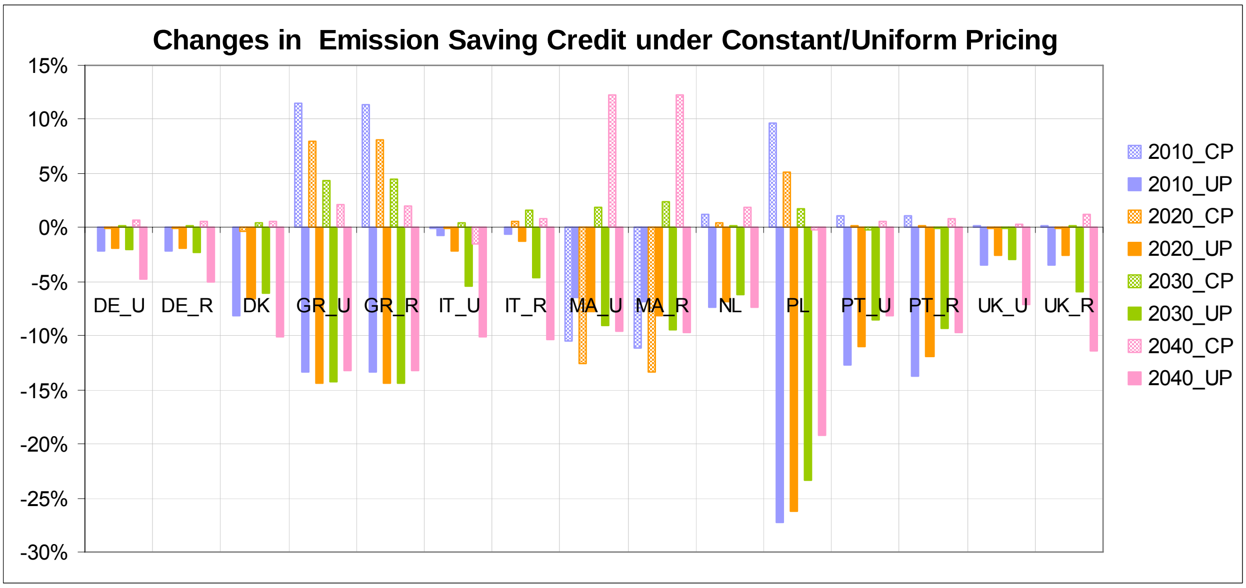


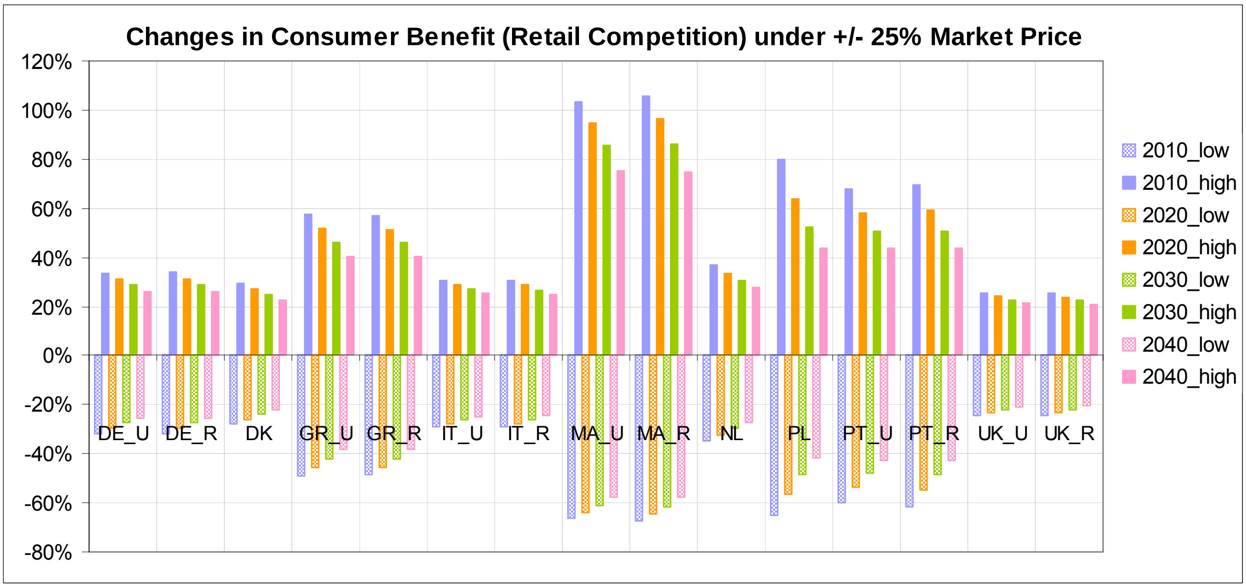
Figure 7-21 Market Price and Pricing Policy Impact on Emission Saving Credit

7.2.4 Economic Benefits: Consumer Side

Potential changes induced by market price variations and pricing policy differences on the selectivity benefit on load side can be seen from Figure 7-22

Firstly, comparison with the original benefit indices in Figure 7-10 shows that countries with lower evaluated benefits under STC setting are found to be more sensitive to mean wholesale price variations—peaked by ± 100% in case of Macedonia. The majority of high-benefit countries under STC find only 20% to 30% benefit variations due to wholesale price level change.

Constant pricing is found to invoke comparatively small impacts over consumer side selectivity benefit in scale of ± 20%—the 100% reduction figures in Macedonia corresponds to 0% usage of MS units due to conversion from real time scheme into a fixed price below MS cost line. Uniform pricing appears to be overwhelmingly effective in boosting the consumer side benefit (up to more than 20 times in 2010) when MS cost is high, but diminishes very fast with passage of time.



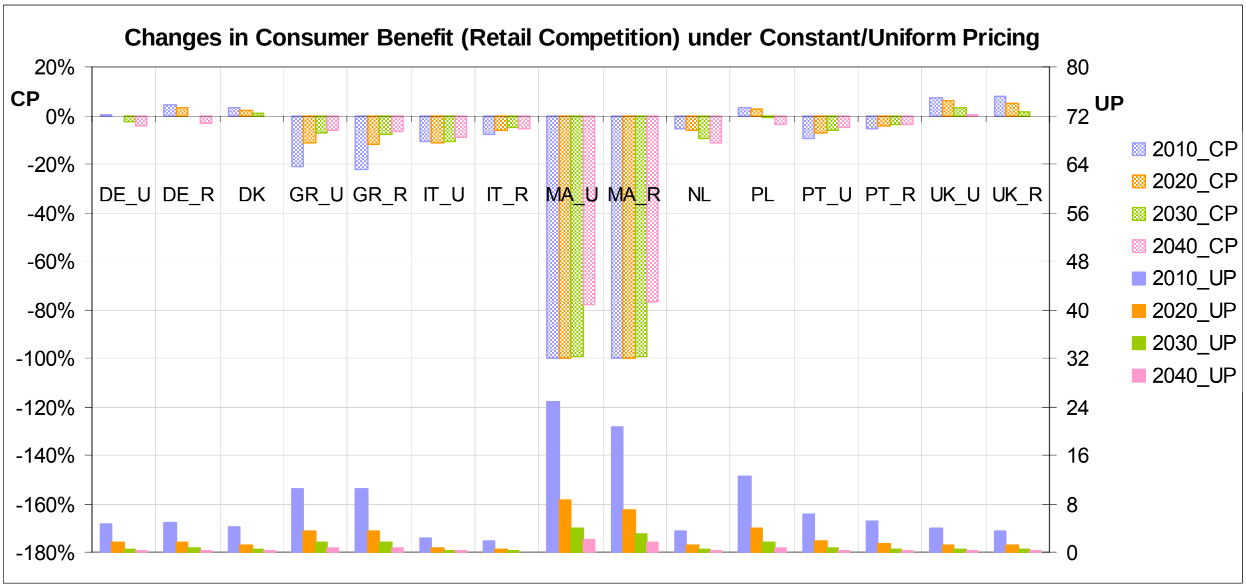
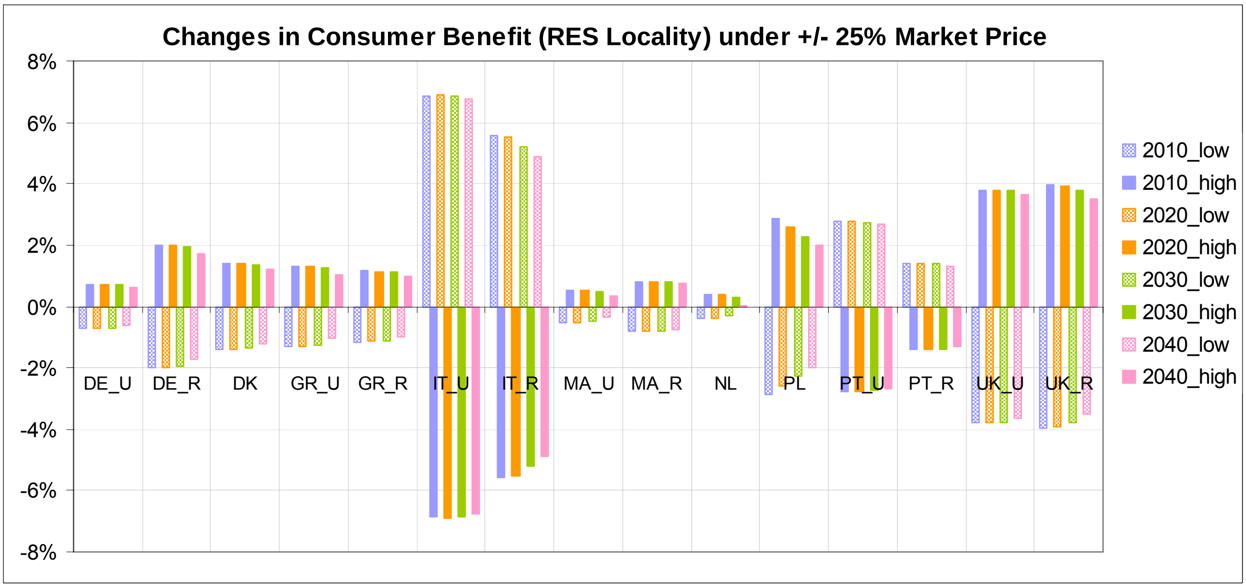


Figure 7-22 Market Price and Pricing Policy Impact on Load Side MS Selectivity Benefit

Potential changes induced by market price variations and pricing policy differences on the RES locality benefit on load side can be seen from Figure 7-23.

Impact of wholesale price level on RES locality value is found to be generally small, falling below ± 6% for most reviewed countries. Decrease of market price is found to reduce RES locality value for 11 tested scenarios and increase RES locality value for the other 4, which justifies the assumption of viewing market price variations to have a negligible impact on load side locality benefit value due to consumption of local RES energy.

Examination of constant and uniform pricing scheme impacts reveals similar small impacts (within ± 15%) for the majority of countries except for the case of Italy, where comparatively higher price variations in wholesale market create higher differences between weighted and non-weighted sums of hourly price in comparison with other countries, which in turn translates into larger errors under different price setting schemes.



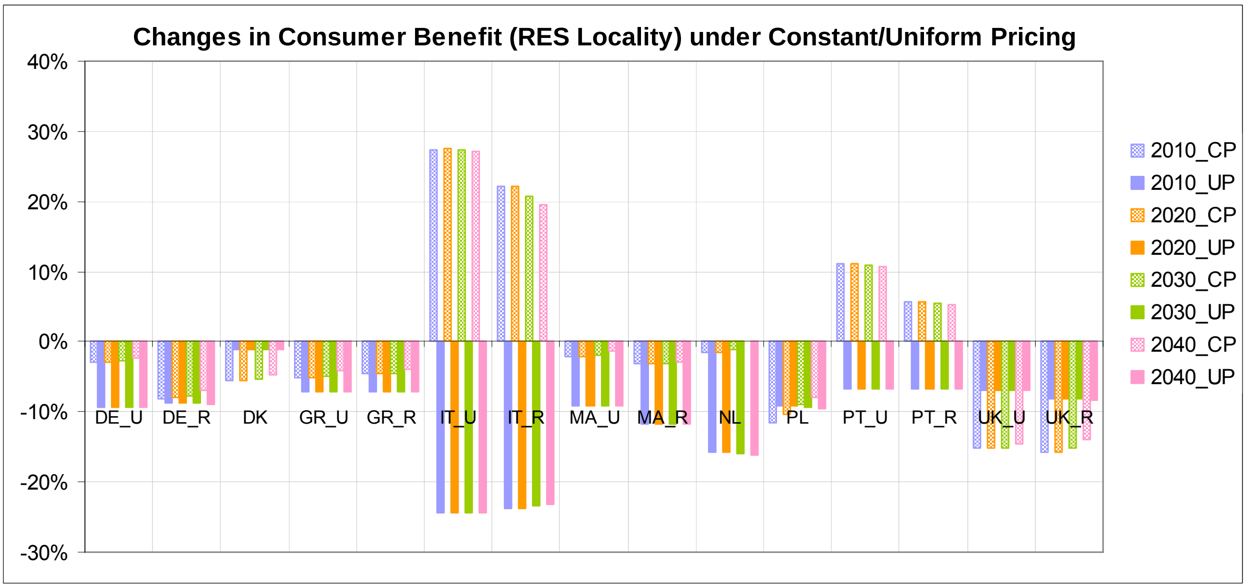
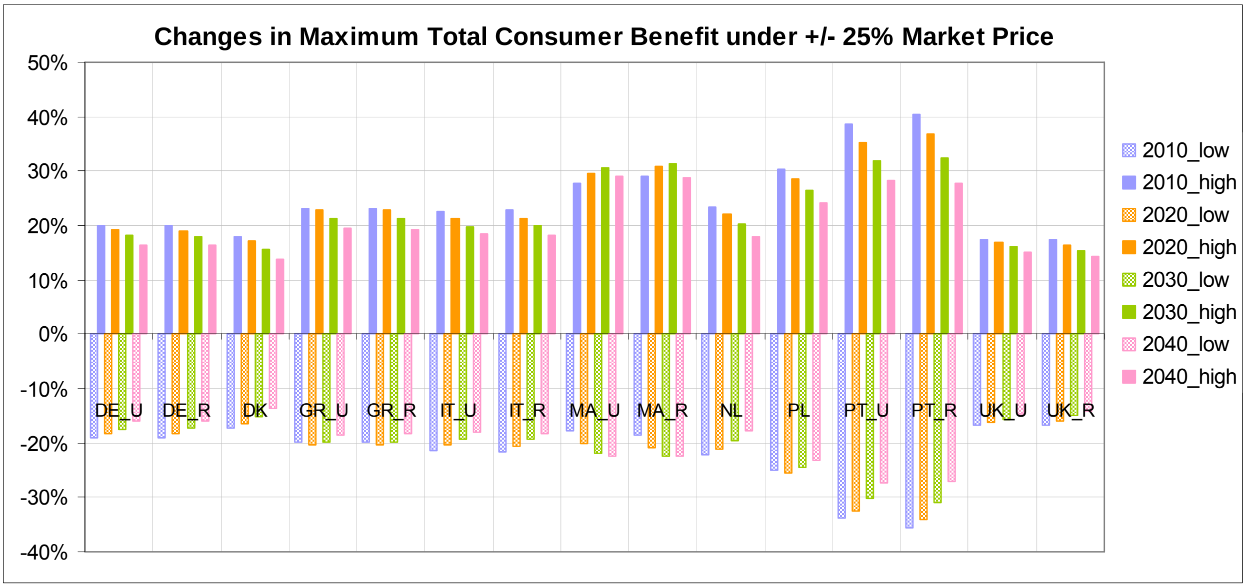


Figure 7-23 Market Price and Pricing Policy Impact on Load Side RES Locality Benefit

Potential changes induced by market price variations and pricing policy differences on maximum total economic benefit on load side can be seen from Figure 7-24.

National differences under the same wholesale price level variation are comparatively small, leading to rather constant values between ± 20% and ± 40% as benefit increase under market price increment and benefit reduction under market price decrement.

Constant pricing is disclosed to have mostly negative impacts over maximum consumer benefit, leading to small benefit reductions below 10% for most countries except for Macedonia, which experiences benefit reduction as high as 35% due to drastic reduction of MS full load hours (even to zero). Uniform pricing could significantly raise maximum total consumer benefit by 2 to 6 times initially in 2010, but their boosting effect quickly fades away with passage of time.



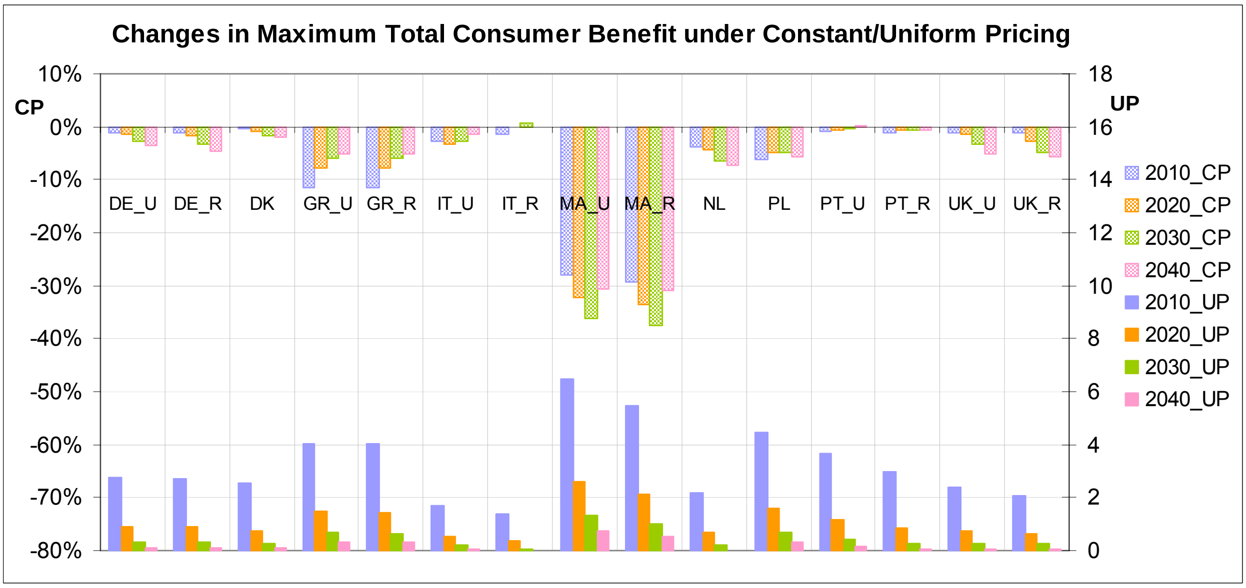


Figure 7-24 Market Price and Pricing Policy Impact on Maximum Load Side Benefit

7.2.5 Economic Benefits: MS Side

Potential changes induced by market price variations and pricing policy differences on locality benefit on MS side can be seen from Figure 7-25.

Clearly, for all simulated cases, increase of mean wholesale price leads to reduction of MS locality benefit (i.e. lower opportune losses if MS units are forced to export) and vice versa. The majority of countries experience variations in order of ± 20% to ± 100% except for Italy, which has variations as high as ± 700% due to its extremely low locality benefit values (MS side) under STC (close to zero).

Constant pricing is revealed to lead to higher locality benefits except for 2010 and 2020 cases of Macedonia, where all dispatchable MS units are shut down for all times. Uniform pricing, on the other hand, is found to be capable of both increasing and decreasing MS locality benefit depending on specific grid and market settings.

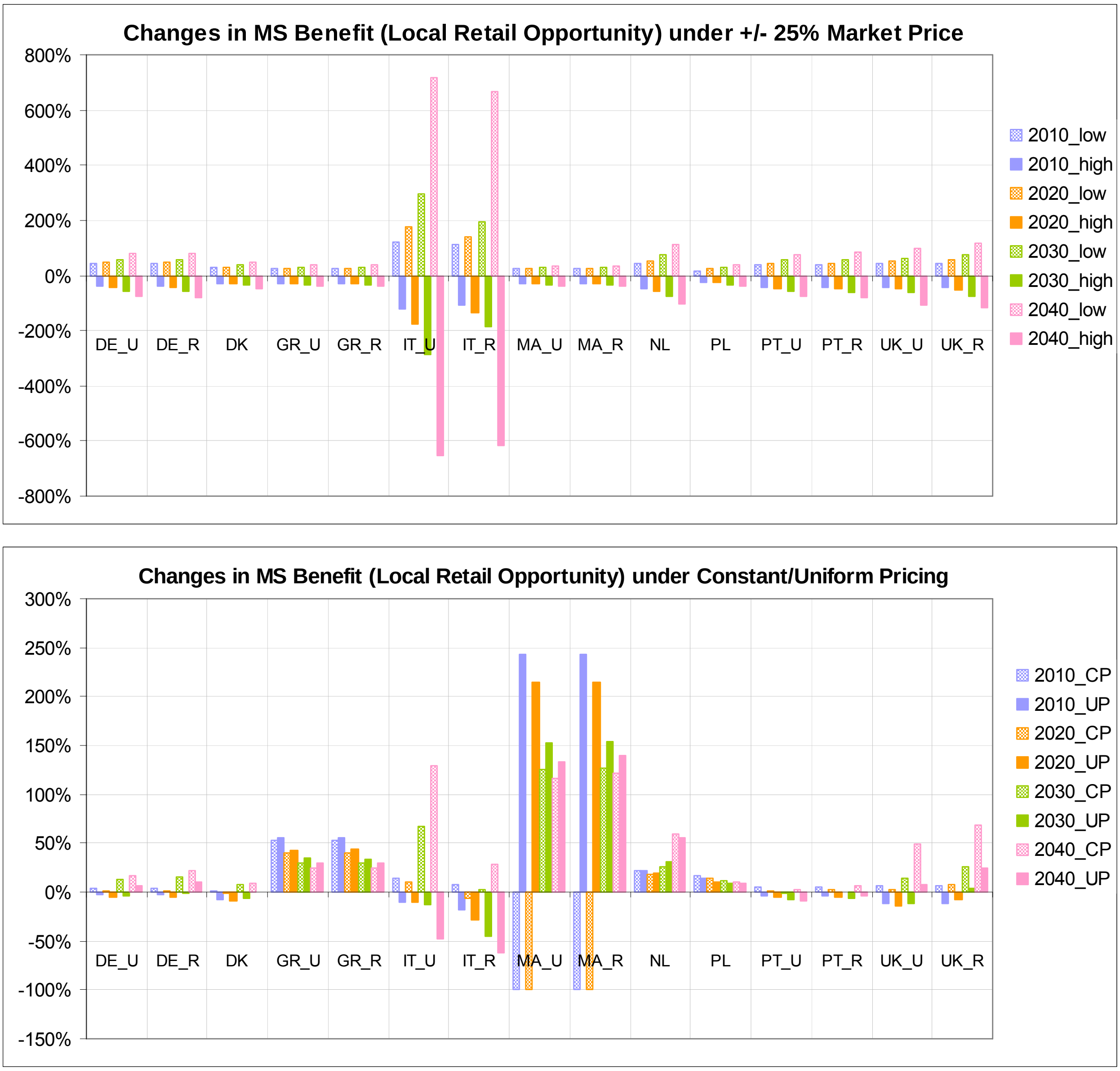
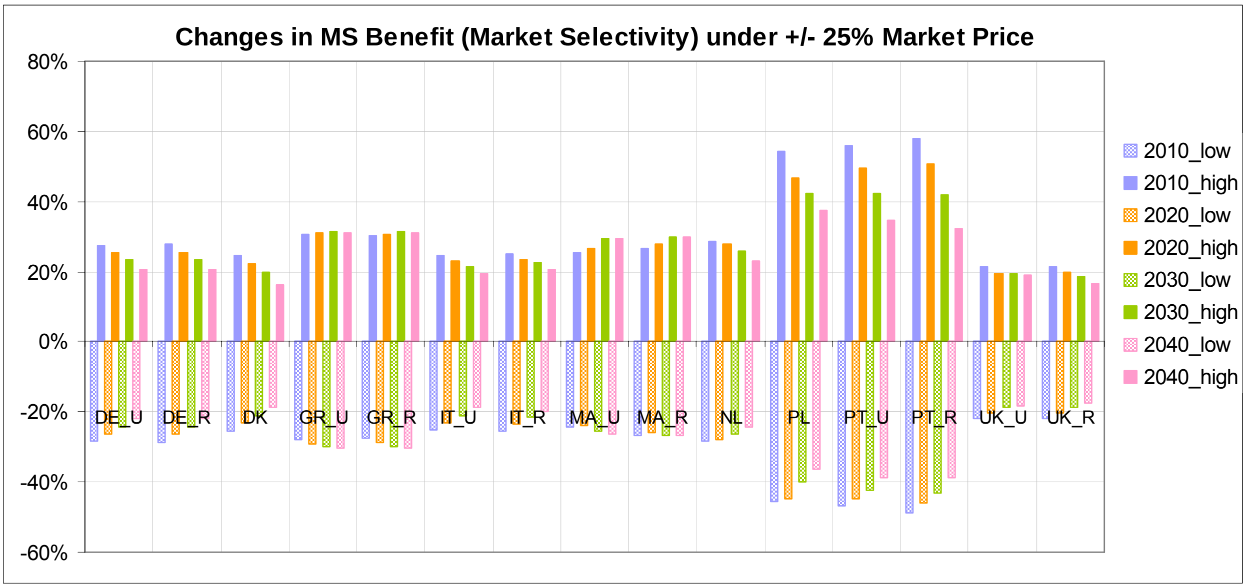


Figure 7-25 Market Price and Pricing Policy Impact on MS Side Locality Benefit

Potential changes induced by market price variations and pricing policy differences on selectivity benefit on MS side can be seen from Figure 7-26

Similar to the results found with consumer side selectivity benefit, the impact of wholesale price level variation on MS selectivity benefit is found to be relatively consistent for all examined countries, falling in general into the range of ± 20% to ± 60%.

Both constant and uniform pricing schemes are found to undercut achievable MS profitability (i.e. selectivity benefit) under most conditions. Constant pricing schemes generally lead to 1% to 30% of profit reduction (in some cases profits are increased by 2% to 7%), while uniform pricing causes 40% to 70% of profit loss for the majority of examined cases.



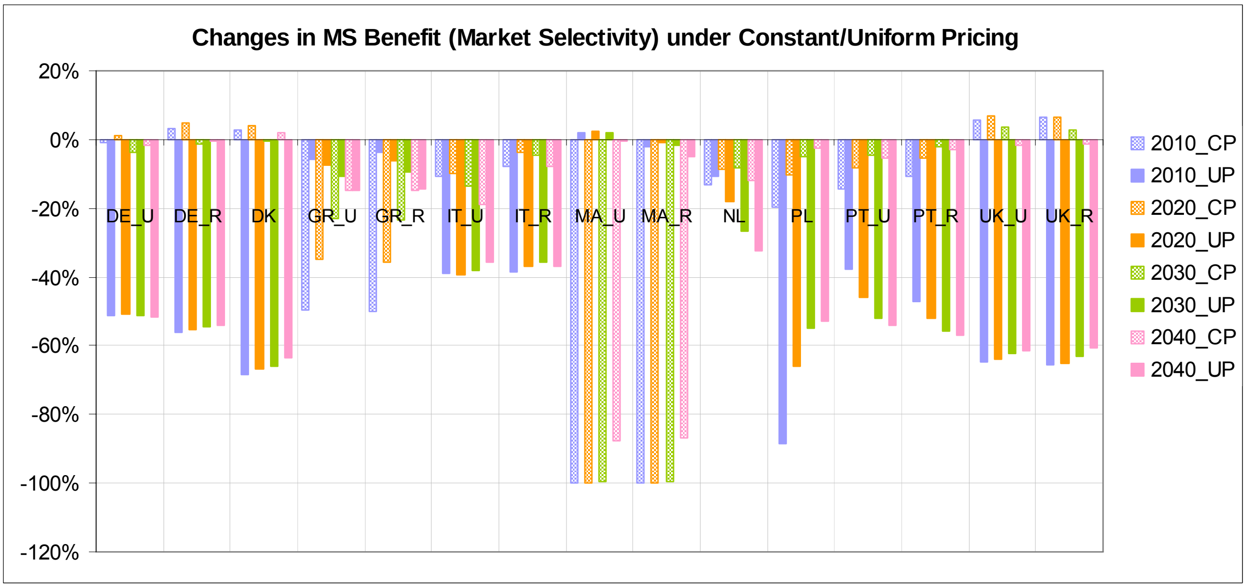
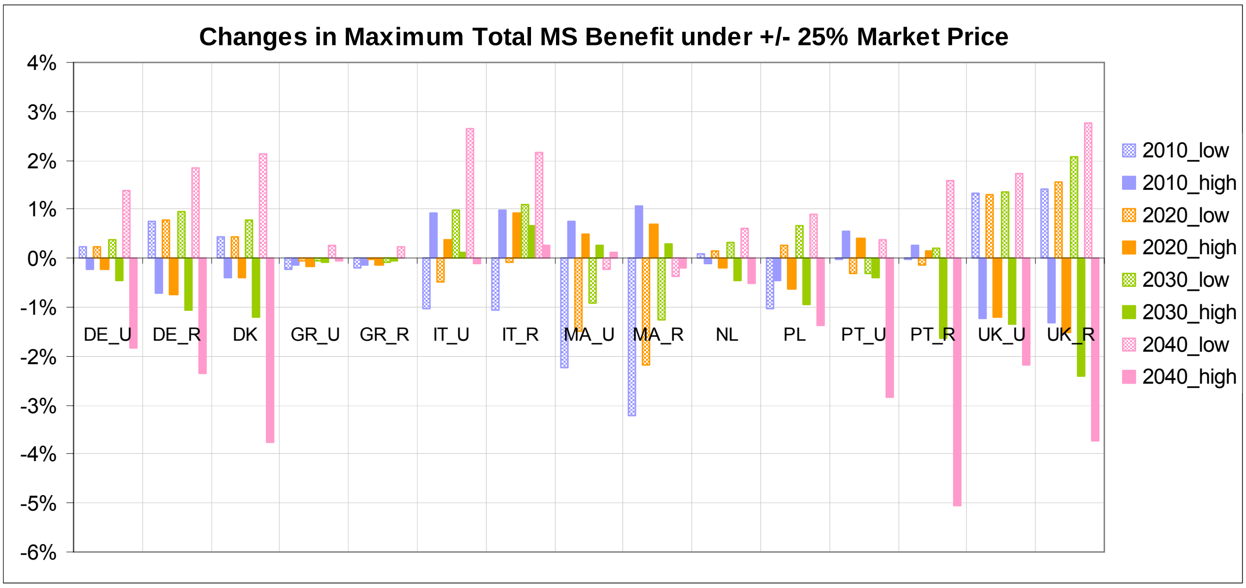


Figure 7-26 Market Price and Pricing Policy Impact on MS Side Selectivity Benefit

Potential changes induced by market price variations and pricing policy differences on maximum total benefit on MS side can be seen from Figure 7-27

As total MS benefit can be almost solely determined by the difference between eventual selling price and average wholesale price in the market, both market price level and constant pricing conversion will basically have negligible impacts (below 5%) on its value. Uniform pricing, however, is potentially capable of changing the mean MS selling price and could therefore lead to total MS benefit changes as high as 50% to 100%.



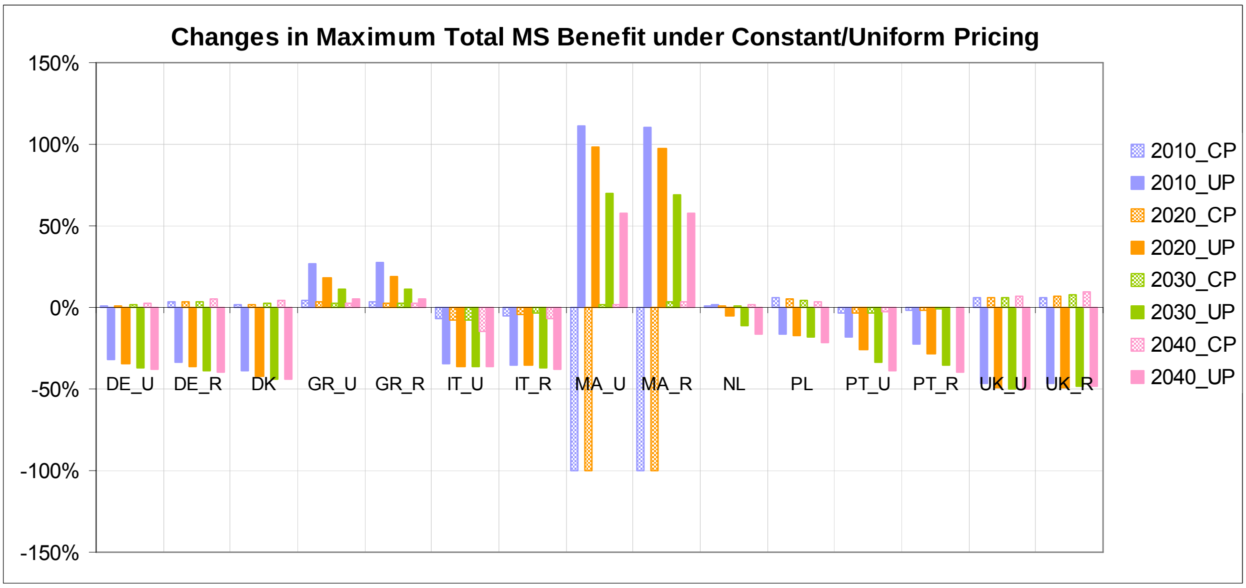


Figure 7-27 Market Price and Pricing Policy Impact on Maximum MS Side Benefit

7.3 Sensitivity Analysis of Microgrid Operation Strategy

In order to avoid the excessive number of simulations to be performed for all defined STC cases, a narrow-down process is required to select a typical time scenario setting so as to justify the application of different Microgrid operation strategies. In Figure 7-28, one sample Microgrid (UK urban) is simulated from 2010 to 2040 cases with all four operation strategies and the maximum total consumer benefit is compared between combined mode and all other three operation strategies. Interestingly, the differences due to operation mode changes are not significant when self supply level of a Microgrid is below 50%. Therefore, for the purpose of European level Microgrid operation strategy impact study, only the 2040 scenarios under STC condition are examined as a consequence.

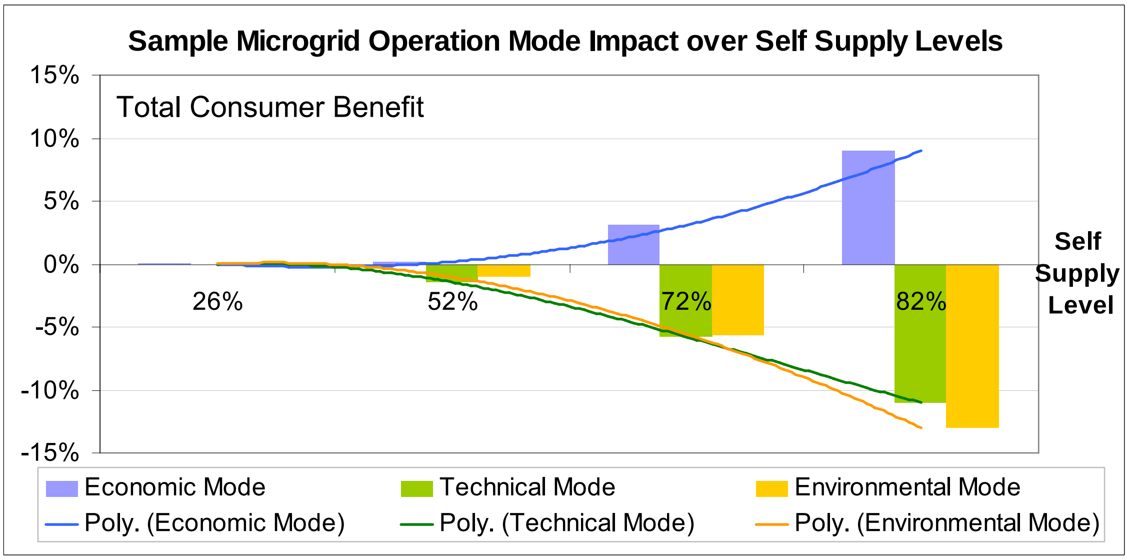


Figure 7-28 Sample Microgrid Operation Mode Impact over Different Self Supply Levels

Obviously, a most balanced set of benefits can be achieved if the combined optimisation method is applied. This can be explained by the fact that although higher benefits for a single objective would arise if DER were optimised only from this specific point of view, other objectives would be very likely worsened as a consequence. According to definitions in section 4.2.2, an economic mode aimed solely at maximizing MS profit, a technical mode aimed solely at minimizing grid energy loss, and an environmental mode aimed solely at minimizing GHG emission from the Microgrid are defined as comparison options hereby to illustrate the necessity of combined optimization. It should be noted that the economic option can be seen as a pure MS aggregator perspective, while the technical mode can be understood as a pure DSO perspective and the environmental mode can be easily translated into an emission regulator perspective.

In order to facilitate illustration, the primary indices for economic, technical, and environmental options are respectively defined as economic benefit (maximum profit per kWh sold energy), annual grid energy loss (kWh per year), and avoided GHG emission (CO2 equivalent per kWh). After enumerating the scheduling outcomes from a number of sample European Microgrids from different countries and regions, the outcomes of each index calculated under all three reference cases are then compared to corresponding values obtained from combined optimization and their relative differences are plotted respectively in Figure 7-29, Figure 7-30, and Figure 7-31 as percentage values.

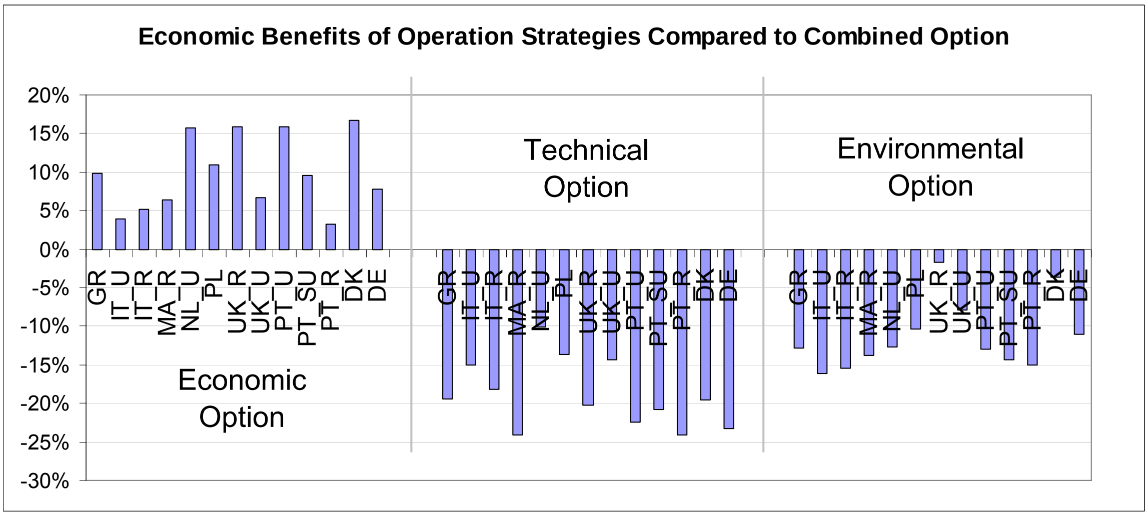


Figure 7-29 Operation Strategy Impact on Maximum Economic Benefits

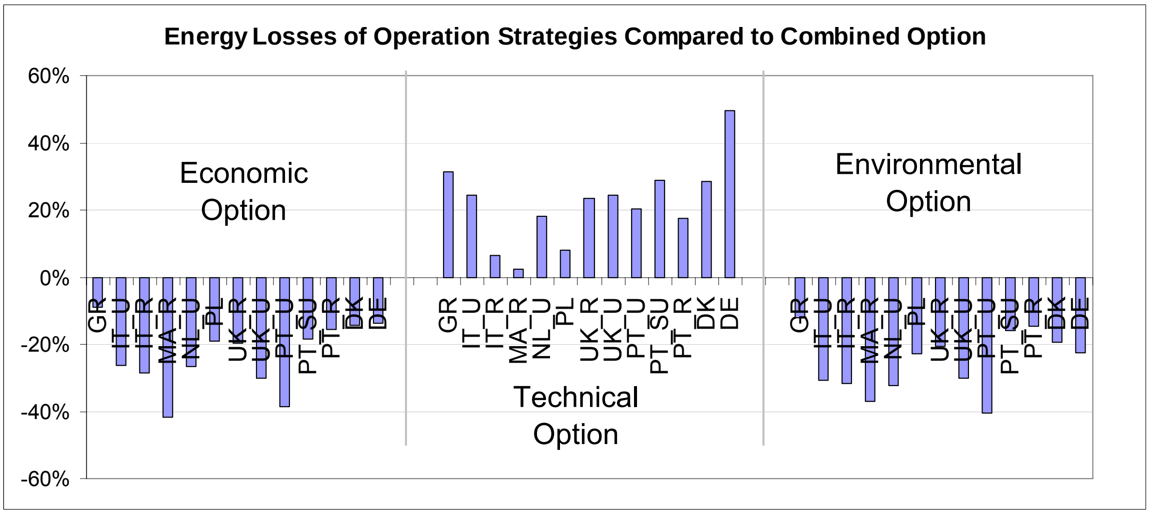


Figure 7-30 Operation Strategy Impact on Energy Losses

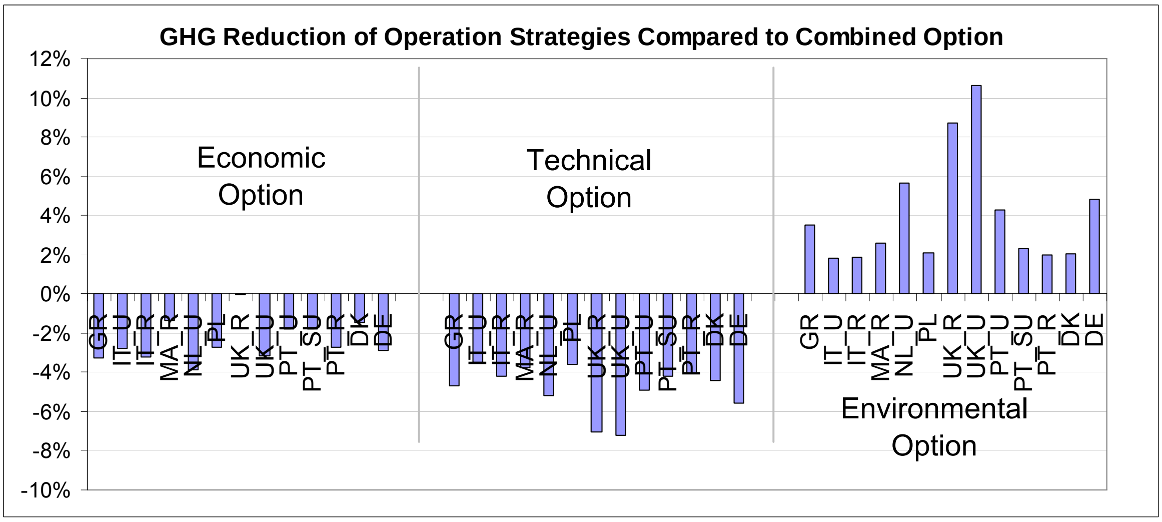


Figure 7-31 Operation Strategy Impact on GHG Reduction Credits

Despite case-wise value variations, all three examined indices reveal the combined option to be the second-best solution coming after the option specifically designed for optimizing the examined index (e.g. economic option for economic benefit index). Thus the combined optimization can be physically viewed as a compromising process where different Microgrid stakeholders co-operate to create a win-win situation so as to arrive at the global optimum point of economic, technical, and environmental performances.

In Figure 7-38 and Figure 7-39, the voltage and loading reduction credits are compared for all examined cases. Quite clearly it can be seen that combined mode can achieve the same level of network performance as technical mode while both economic and environmental modes fail to do so.

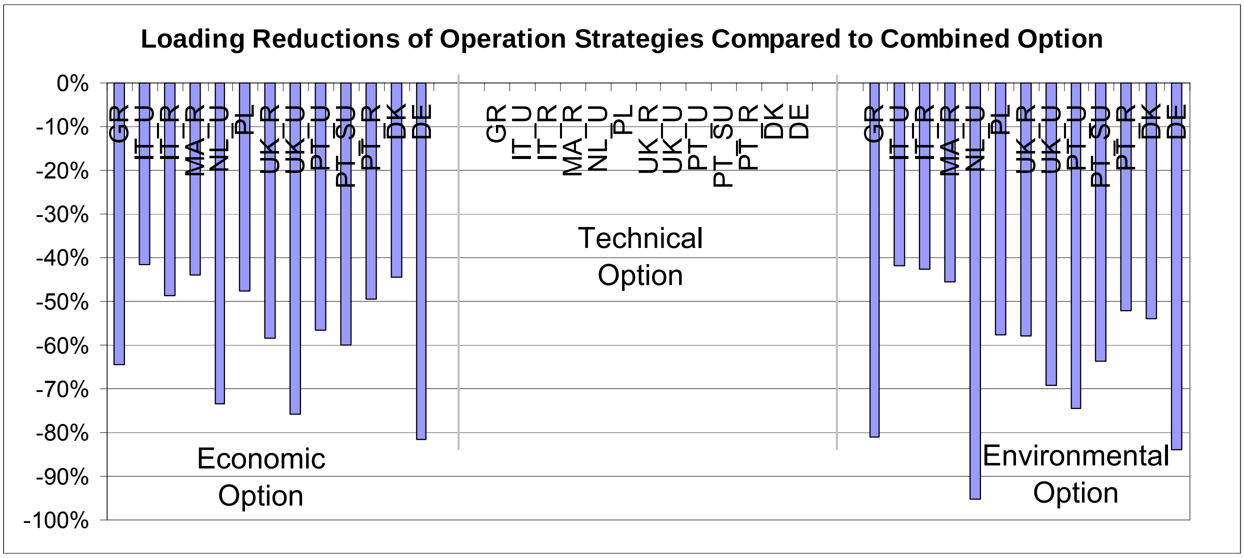


Figure 7-32 Operation Strategy Impact on Loading Reduction Credits

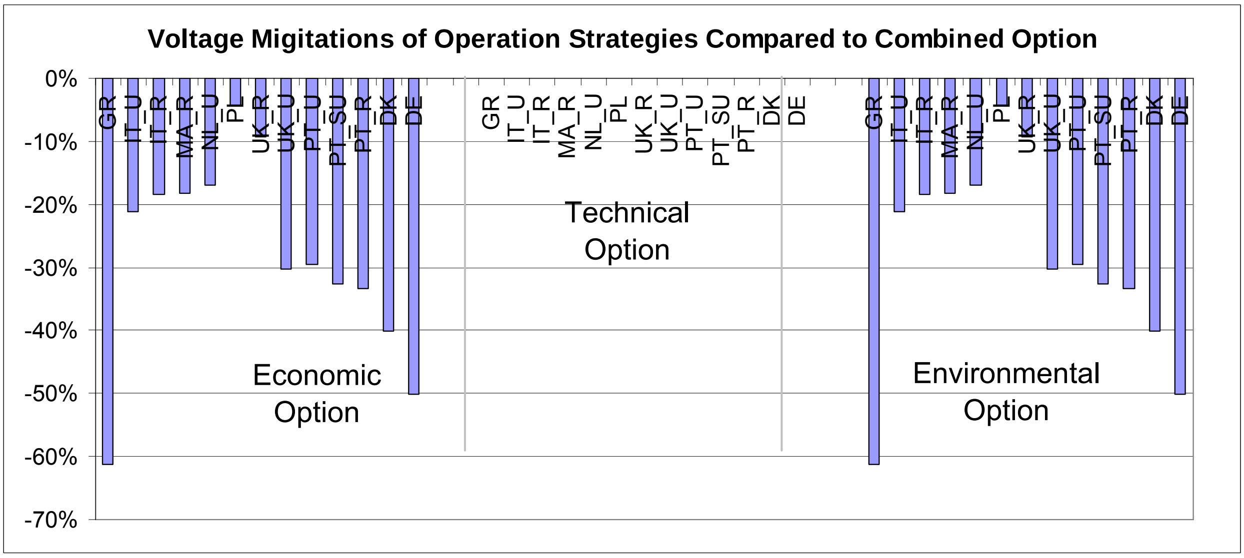


Figure 7-33 Operation Strategy Impact on Voltage Variation Reductions

7.4 Reconciliation with Partners' Contributions

Based on the typical network data identified in DG1 separate studies have been performed by different partners. While the findings presented in this deliverable are mainly based on simulations done by Siemens AG, Annex 5 provides a 'Report on Technical, Economic and Environmental Benefits of Microgrids on Power System Operation' according to a study performed by INESC Porto. Annex 6 contains a 'Report on Economic Benefits of Microgrids'; this is a study performed by NTUA.

Reconciliation with Study performed by NTUA

NTUA part of Reconciliation data are taken directly from Annex 6. Siemens results are based on STC simulation.

Two basic (load side) self sufficiency levels have been assumed by NTUA, namely policy 1 (MS units serve all three feeders in LV grid) and policy 2 (MS units serve only residential feeder). The former case can be seen as close to the previously assumed 2020 Greek case, while the latter one can be seen as similar with the 2040 Greek case (both taken as urban data). In Figure 7-34, this comparison is provided in graphical format.

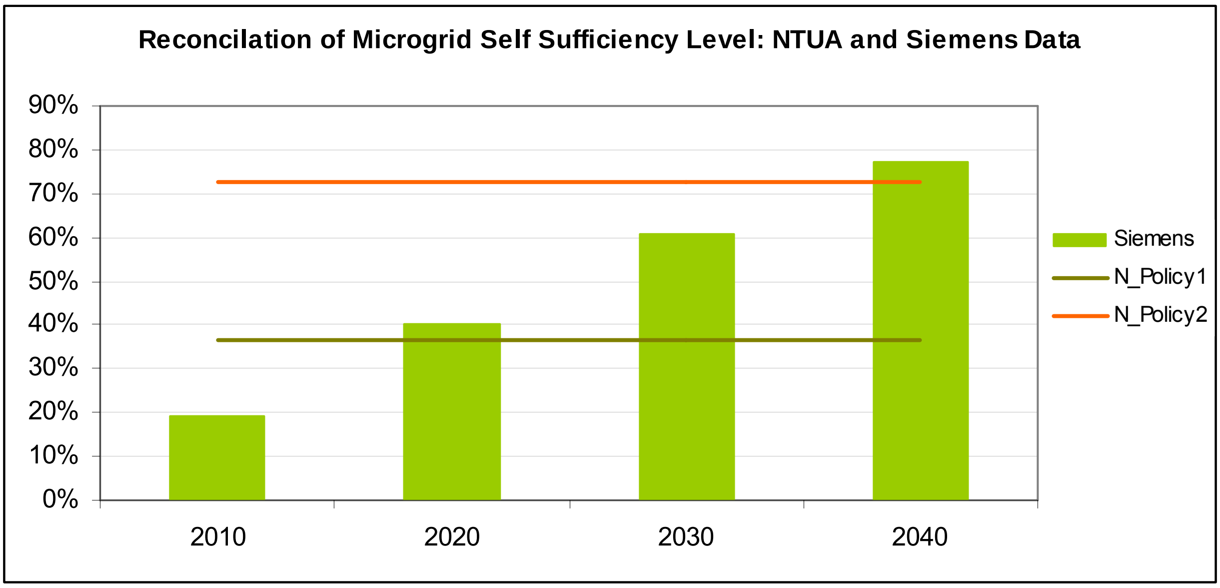


Figure 7-34 Reconciliation of Microgrid Scenario Definition

As price volatility has been assumed to be extremely high by NTUA, from Siemens side (data used for main report) only the average (mid) market price scenario is taken for comparison. However, comparing the annually accumulated data from both NTUA and Siemens under low-benefit, mid-benefit, and high-benefit conditions exhibits relatively good constancy in general.

In Figure 7-35, consumer side price reduction credits are compared from both sources. Since NTUA results are calculated assuming policy 1 scenario, the closest match from Siemens result is the 2020 case. Comparison shows that results from both sides converge with small deviations under low-benefit and mid-benefit conditions, while NTUA estimation of price reduction credit under high benefit setting seems to be more pessimistic than Siemens result despite of having applied different tools.

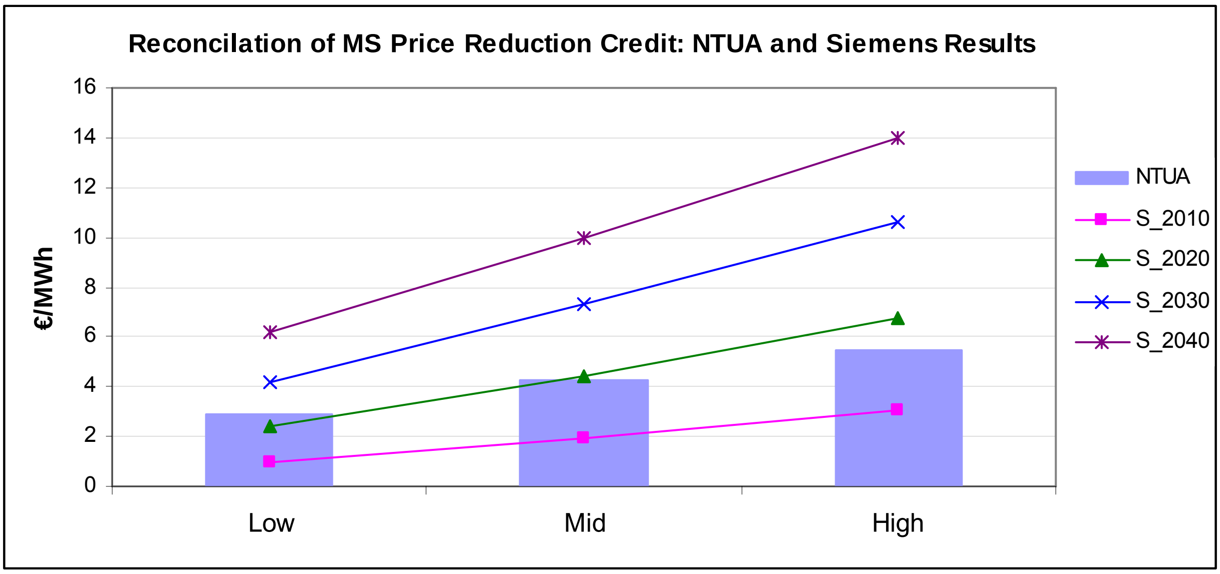


Figure 7-35 Reconciliation of Microgrid Price Reduction Credit

In Figure 7-36, per MWh benefit data from MS export are compared similarly between NTUA and Siemens results. As this part of study has been performed by NTUA under policy 2, the closest scenario from Siemens is the 2040 case. Comparison indicates good convergence at high-benefit conditions but much lower Siemens results compared to NTUA under low- and mid-benefit conditions. This can be mainly explained by higher ratios of dispatchable MS/RES from NTUA in comparison with Siemens data.

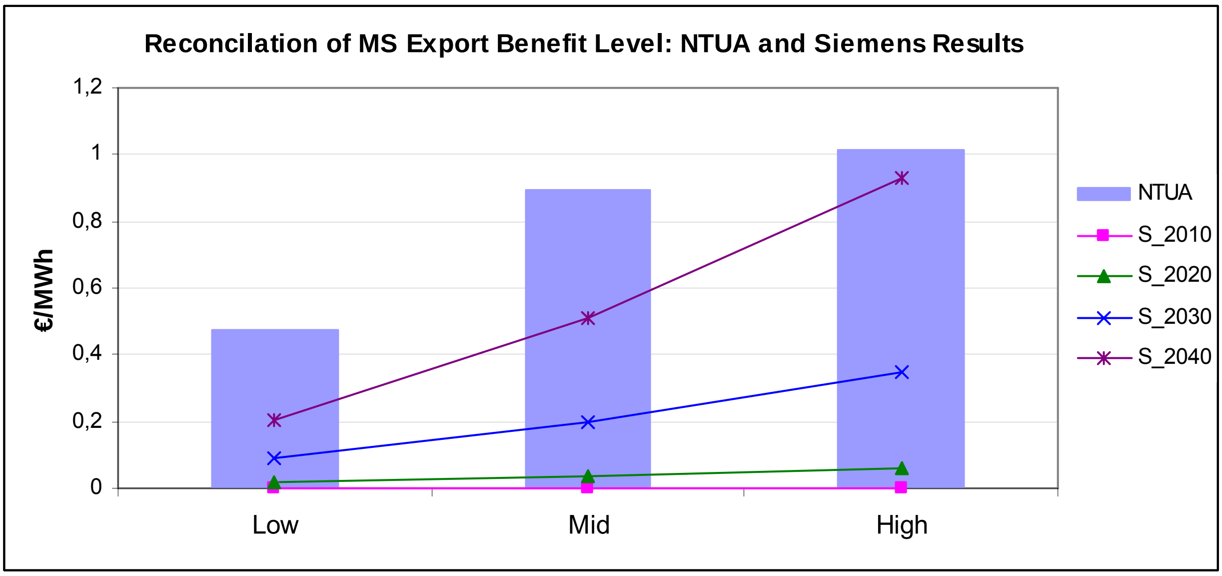


Figure 7-36 Reconciliation of MS Export Benefit Level

In Figure 7-37, loss reduction credits from NTUA (policy 1) and Siemens (2020 and 2030) results are compared. IT can be seen that maximum credit (all full production, MT bus =>8) from NTUA falls in between 2020 and 2030 results from Siemens.

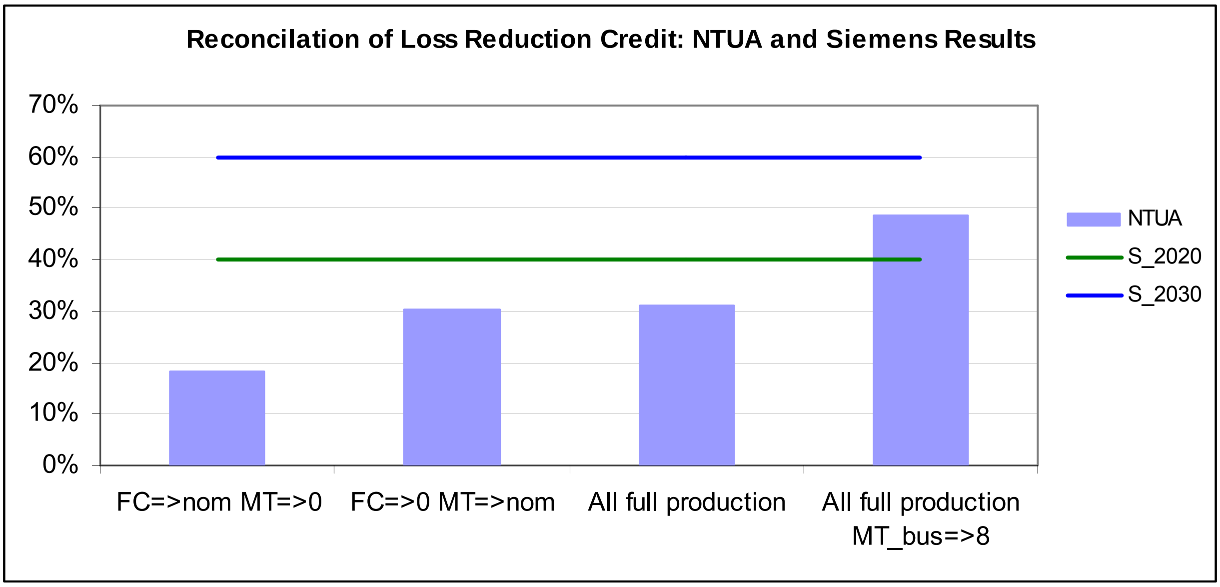


Figure 7-37 Reconciliation of Microgrid Loss Reduction Credit

Finally, emissions saving credits from both sources are compared in Figure 7-38. The low- and high-benefit scenarios from NTUA are respectively based on 20€/MWh and 60 €/MWh emission charges. Comparison shows NTUA low-benefit result under SCE 3 close to Siemens 2020 case and NTUA high-benefit result under SCE 3 close to Siemens 2030 case.

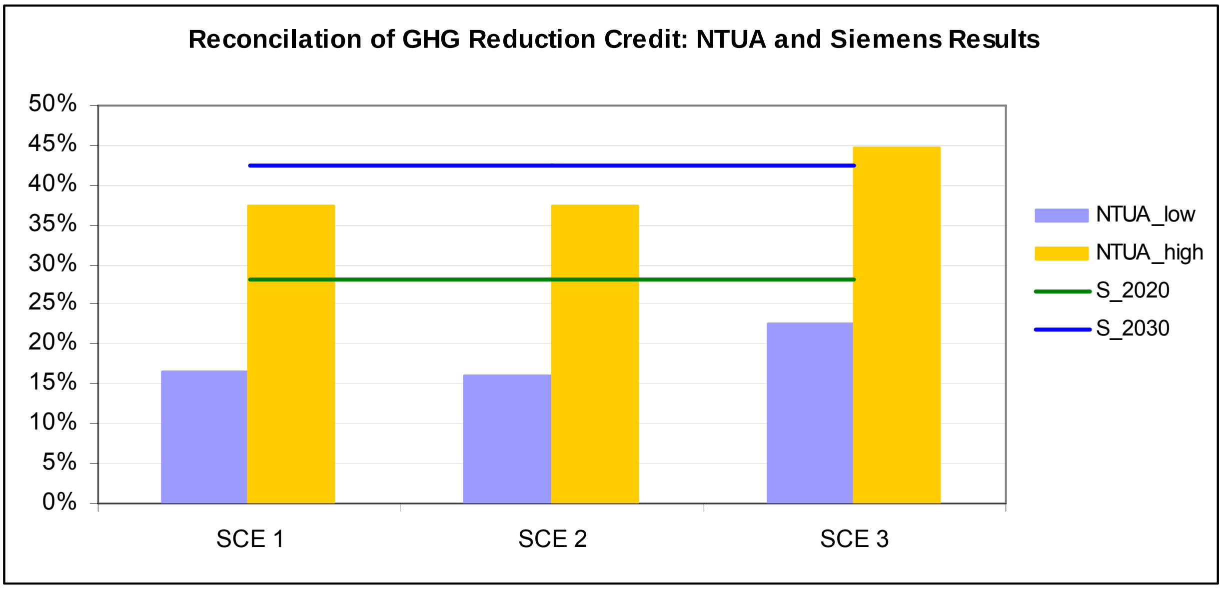


Figure 7-38 Reconciliation of Microgrid GHG Reduction Credit

Reconciliation with Study performed by INESC

A reconciliation of Siemens results with INESC result is included in Annex 5. Their main findings – as described below – correspond with other partner's evaluation.

High electricity market prices yield controllable micro-generation dispatch and controllable load shifting at each Microgrid network level (MGCC control level) due to price responsiveness and detection of overall benefits due to a local optimization procedure at each MGCC control level. Moreover, activation of load curtailment contracts for the controllable load within each MG and controllable micro-generation dispatch under CAMC may account for the technical constraint resolution (congestion relief) as well as in high market prices periods, due to a significant controllable load reconnection to an hour of low electricity market price (within the shift option, at each MGCC level).

In general, higher percentage of micro-generation, controllable or not, leads to higher overall benefits. Moreover, winter time periods favours higher percentage of controllable micro-generation installed capacity (in low and high electricity prices periods) over the non-controllable (PVs) due to poor sun radiation during winter.

The study of the Portuguese transmission network demonstrated that the influence on active power losses resulting from the presence of microgeneration at the distribution level is significant and grows with the percentage of microgeneration. Annual energy losses in the transmission system can be reduced up to 10%, namely when the microgeneration penetration reaches 30% of the peak load of the domestic consumption. Such benefits clearly demonstrate the positive effects that microgeneration might bring to the transmission system resulting from the effect of load reduction at the distribution level.

7.5 Extension to General European Scale

In Figure 7-39, a summary of maximum total consumer benefit is shown with general European status projection. It can be seen that benefit increases with Microgrid self supply level and reaches about 35 ± 25 €/MWh at 90% (load) self supply ratio. This maximum benefit is the sum of potential price reductions due to local trading as well as network and emission charge reductions. The shown values, however, are based on the assumption that all economic benefits are obtained by end consumer; while in reality MS units, DSO, and potential intermediary parties are very likely to share this total benefit, leading to splitted economic indices with lower values.

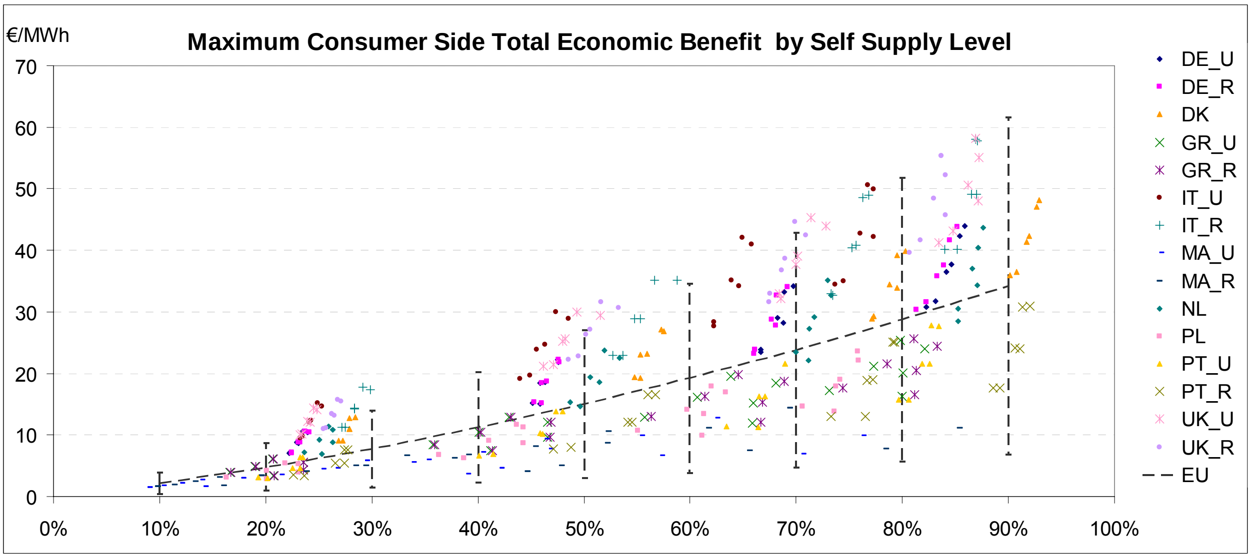


Figure 7-39 Summarized Total Consumer Benefit under European Context

In Figure 7-40 a summary of maximum consumer benefit due to retail market selectivity is shown with general European projection; and about 30 ± 20 €/MWh benefits can be observed when dispatchable MS units can supply 50% of Microgrid demand (i.e. the same time as 90% total self supply level). Comparison with Figure 7-39 indicates that economic values created from market selectivity are expected to represent higher shares of total benefit as self supply level rises.

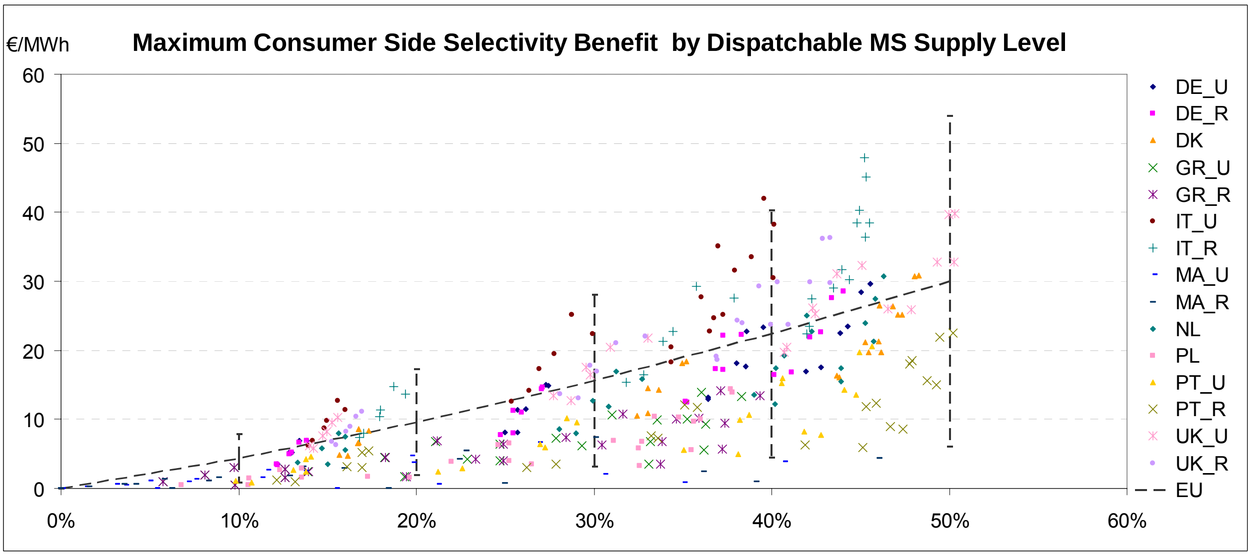


Figure 7-40 Summarized Consumer Benefit due to MS Selectivity under European Context

In Figure 7-41 a summary of maximum total micro-source benefit is shown with general European projection, from which about 60 ± 30 €/MWh benefits can be observed. Obviously, this level of benefit is largely independent of Microgrid self supply level, as the total economic benefit on MS side is solely determined by the gap between wholesale and retail price levels applicable to Microgrid environment. Similar to the consumer side benefit indices, actual benefits received at MS side are likely to be smaller than the plotted data due to interest allocation possibilities.

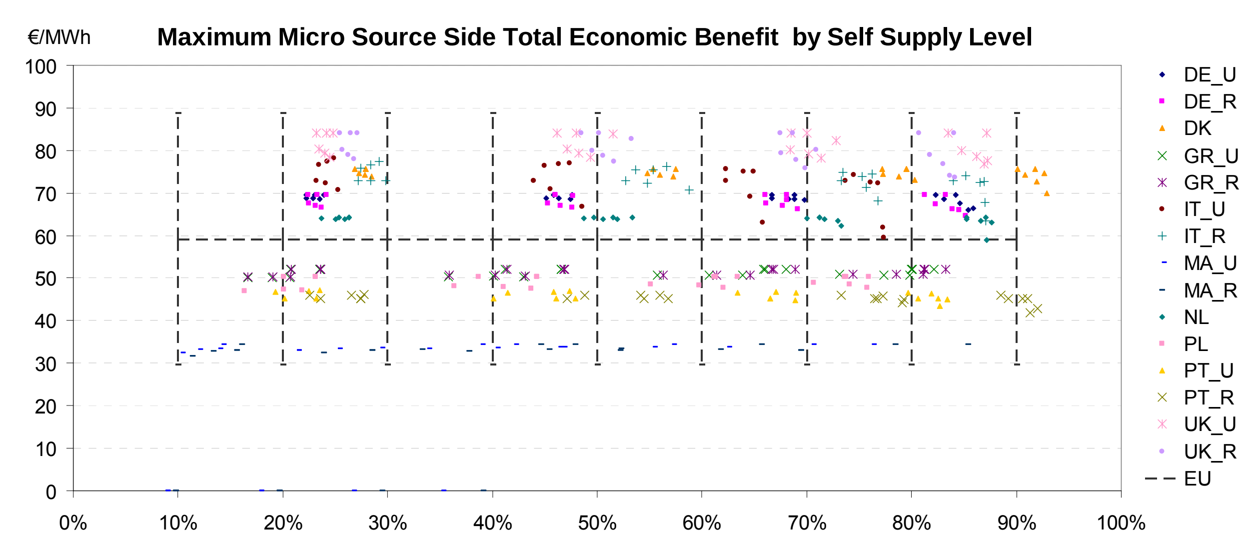


Figure 7-41 Summarized Total MS Benefit under European Context

In Figure 7-42 a summary of maximum MS selectivity benefit (maximum profit margin) is shown with general European projection, from which about 45 ± 40 €/MWh benefits can be expected at all conditions. As already explained in section 5.4.1.2, the selectivity benefit index can be viewed directly as the potential profit margin of a dispatchable MS unit under Microgrid operation. Thus the wide range of potential profitability shown by Figure 7-42 corresponds directly to the market, policy and regulatory differences applied to defined test Microgrids.

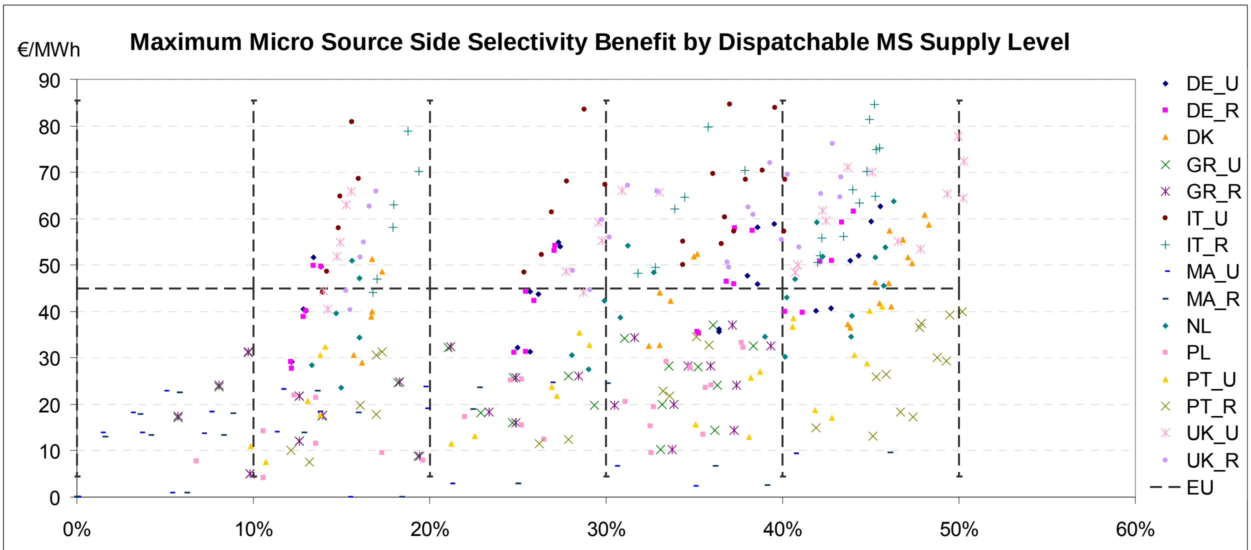


Figure 7-42 Summarized MS Benefit due to Selectivity under European Context

In Figure 7-43 a summary of ideal loss reduction credit is shown with general European projection, about 75% ± 20% benefits can be expected at 90% self supply level.

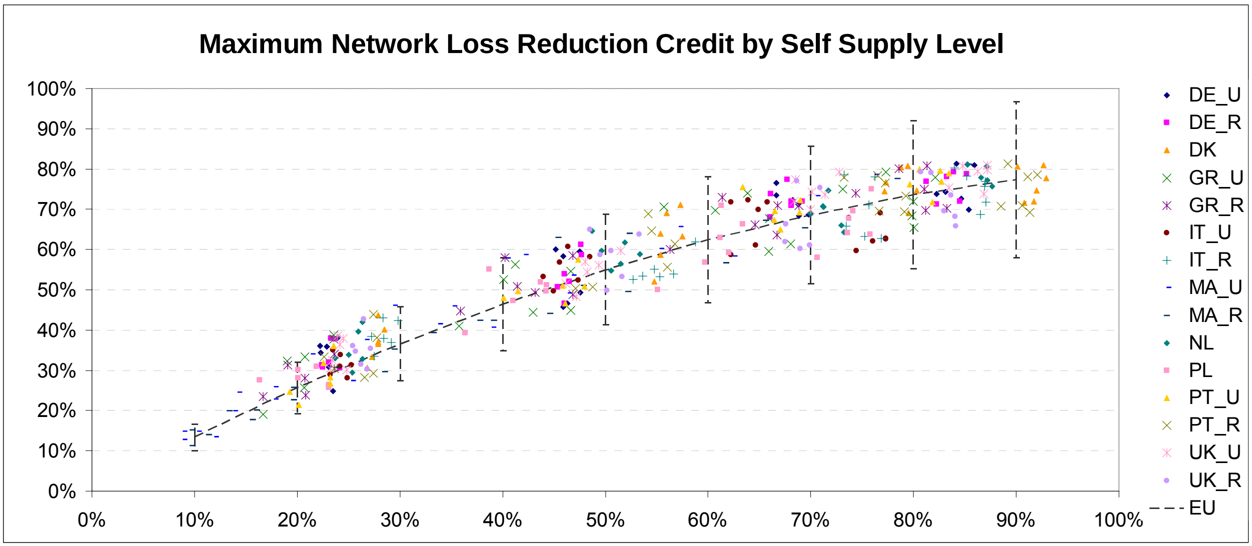


Figure 7-43 Summarized Loss Reduction Credit under European Context

In Figure 7-44 a summary of ideal voltage regulation credit is shown with general European projection, about 50% ± 15% benefits can be expected at 90% self supply level.

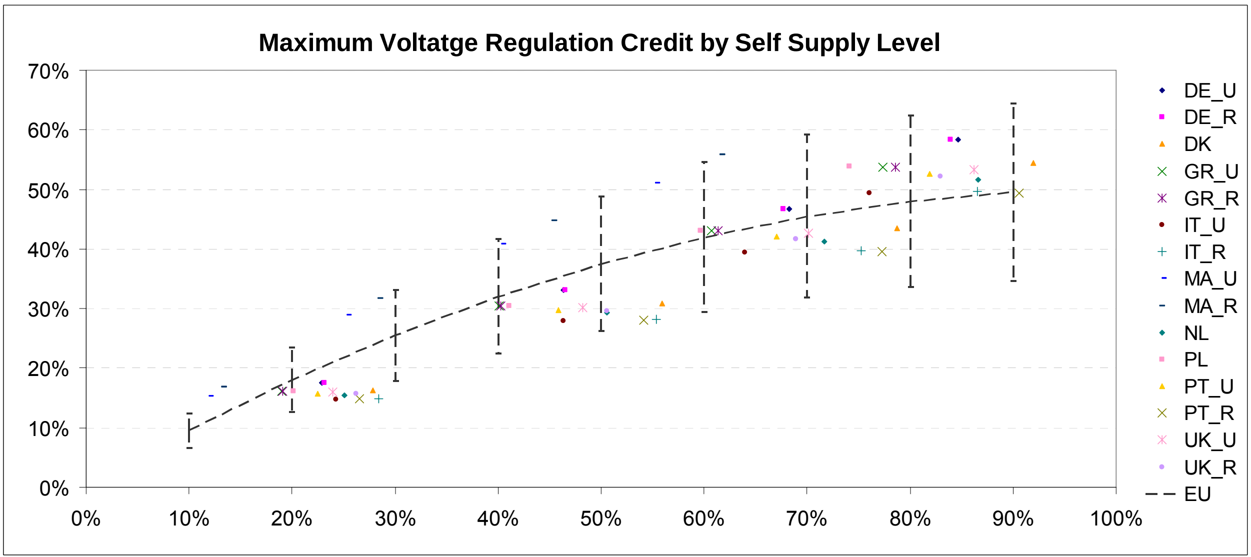


Figure 7-44 Summarized Voltage Regulation Credit under European Context

In Figure 7-45 a summary of ideal peak load reduction credit is shown with general European projection, about 40% ± 12% benefits can be expected at 90% self supply level.

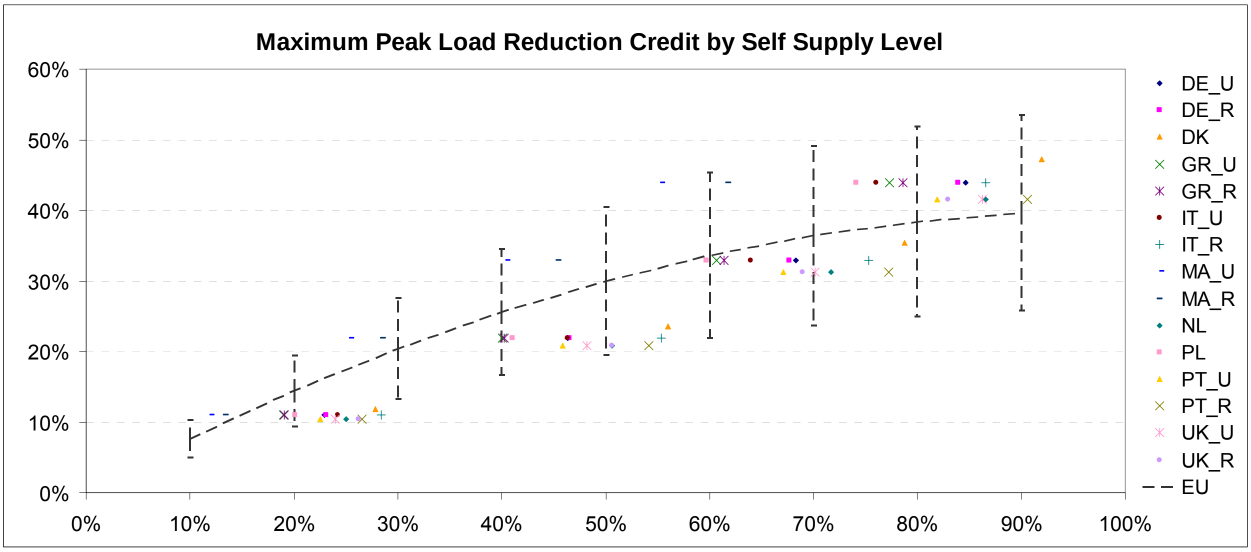


Figure 7-45 Summarized Peak Load Reduction Credit under European Context

In Figure 7-46 a summary of GHG reduction credit is shown with general European projection, about 55% ± 25% benefits can be expected at 90% self supply level.

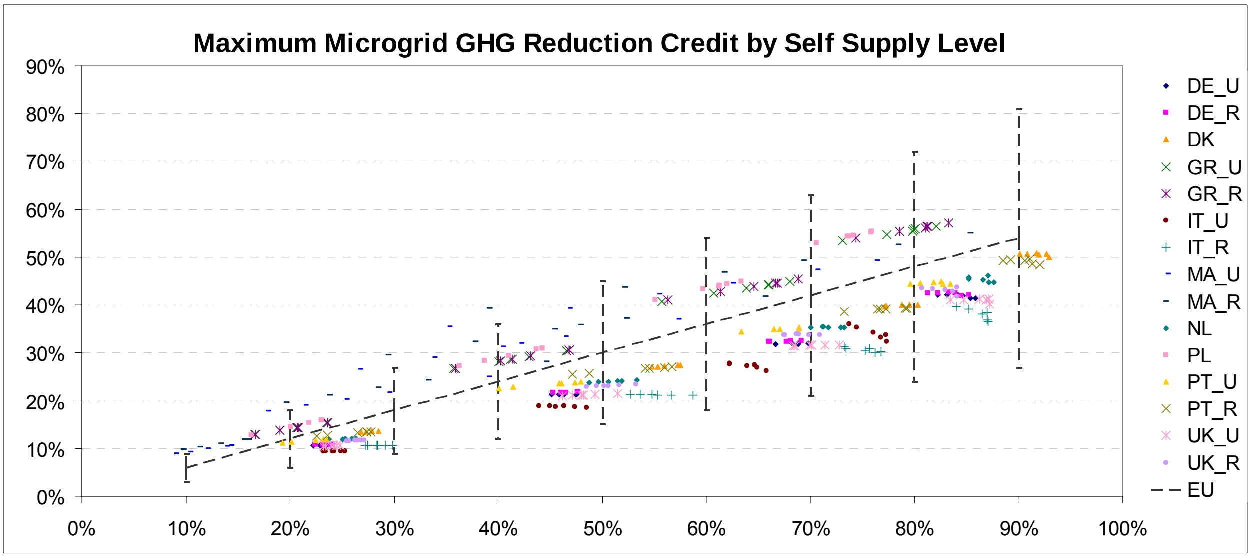


Figure 7-46 Summarized GHG Reduction Credit under European Context

In Table 7-1 to Table 7-4, the expected level of RES premium supports are respectively shown from 2010 to 2040 cases.

Red colour refers definitive need of financial support;

Yellow colour refers to marginal condition where need for external support is very small;

Green colour refers to complete RES entry into free market within Microgrids;

L refers to low market price, M refers to mid market price, and H refers to high market price;

The majority of high-price countries will be able to withdraw financial supports for almost all RES options except for PV by 2030; by 2040 even the PV support can be retracted in these countries. Countries with lower electricity prices are basically only capable of introducing micro wind turbines to the competitive free market by 2030/2040.

Table 7-1 Required RES Support Level Estimation for 2010

Table 7-2 Required RES Support Level Estimation for 2020

Table 7-3 Required RES Support Level Estimation for 2030

Table 7-4 Required RES Support Level Estimation for 2040

8 Conclusions and Recommendations

8.1 General Conclusions

A Microgrid is capable of overcoming conflicting interests of different stakeholders and achieving a global socio-economic optimum in operation of distributed energy sources.

Economic, technical, and environmental impacts of a Microgrid are intertwined together as simultaneous outcomes of MS, storage, and DSI operation decisions; thus extensive communications are needed among these individual entities so as to maximize the potential benefits from a Microgrid.

Proper planning of a Microgrid requires knowledge and simulation of its actual operating conditions; while in the mean time different planning decisions (especially referring to DG/RES penetration level) will lead to different levels of potential benefits that the Microgrid could bring about.

Main findings from WPG can be summarised as:

1. Microgrid can be **profitable** to invest and operate given the current market situation in EU. However, a suitable regulatory framework including proper policy and financial support need to be available.
2. Microgrid offers a **local market** opportunity for 'over-the-grid' energy trading between Micro Sources and end consumers.
3. Microgrid can **maximize total system efficiency** as it represents the interests of Micro Sources, end consumers, and local LV grid as a whole.
4. Microgrid allows for real time, **multi-objective dispatch** optimization to achieve economic, technical, and environmental aims in the same time.
5. Microgrid can accommodate different ownership models and provide **end consumer motivation** where other concepts fail to do so.
6. Microgrid can **accelerate commercialization** of RES units such as PV.

8.2 Roadmap for Microgrid Development

In Figure 8-1, an exemplary roadmap for Microgrid development in Europe is suggested.

Up to now, **cost, policy, and technology** barriers have largely restrained Microgrids inside laboratories with little commercial appeal or social recognition. However, these three barriers are subjected to considerable uncertainties in future, which means they are also very likely to turn into key enablers as time moves on, eventually leading to widespread Microgrid adoption across Europe.

Firstly, cost factor should prove to be the most effective driving force for Microgrids in the very immediate future. This includes not only reduction of MS generation costs within a Microgrid, but also relative changes of external opportune costs due to economic (market fluctuation), technical (network aging), and environmental (emission trading) causes. Obviously, pure economic law (i.e. profitability) is the basic prerequisite for a Microgrid to step from laboratory into reality.

Once cost signals have lead to a noticeable amount of MS penetration in a LV grid, participants in the electricity retail business will start to view the aggregated small generators as a new entrant to the market. Unlike VPP, Microgrid stakeholders will eventually identify a new feature on the aggregated MS units—locality: the MS units can potentially sell directly to end consumers in an 'over-the-grid' manner. In order to turn this potential into reality, however, the second factor—policy and regulatory settings—need drastic modifications from concurrent status to enable the local market within a Microgrid.

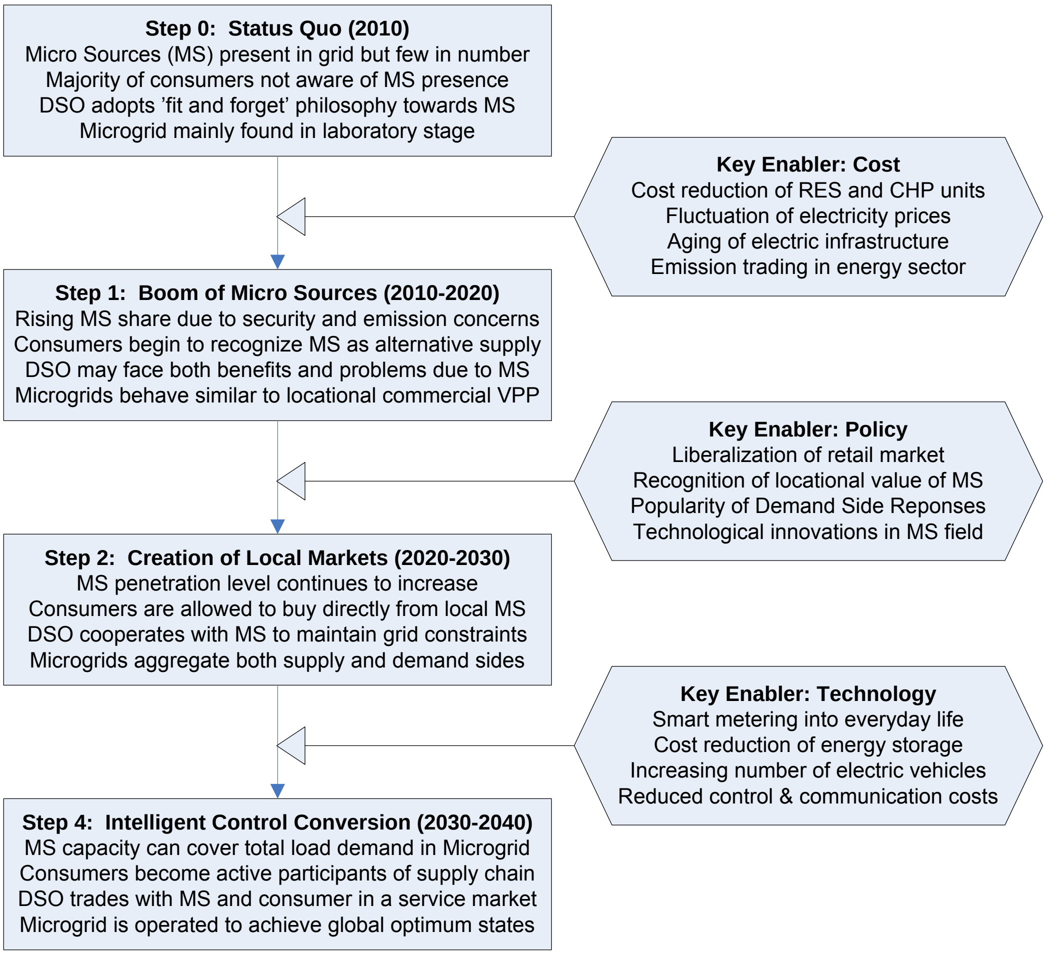


Figure 8-1 Roadmap for European Microgrid Development

Finally, after the appeal of better selling price at local retails markets attracted even more MS units to a Microgrid to the point of allowing island operation, the final challenge of scheduling and dispatch optimisation will be posed to Microgrid operator. With the help of smart metering, control, and communication technologies, a Microgrid operator will be eventually able to coordinate a large consortium of intermittent and controllable MS units as well as central and distributed storage devices to achieve multiple objectives and cater to the interests of different stakeholders in the same time.

8.3 Summary of Benefits from Microgrids

Economic Benefits of Microgrid Operation

A Microgrid could potentially offer (single or multiple from list):

- Price reduction for end consumers,
- Revenue increment for Micro Sources,
- Investment deferral for Distribution System Operators

The listed economic benefits arise mainly from **locality values** created by local retail market and **selectivity values** created by optimized real time dispatch decisions

To achieve expected economic benefits, the following are suggested:

- Recognition of local (‘over-the-grid’) energy trading within a Microgrid
- Application of real-time import and export prices for Microgrids
- RES support scheme and favourable tariffs (optional)

Summary of Technical Benefits of Microgrid Operation

A Microgrid could potentially offer (single or multiple from list):

- Energy loss reduction,
- Mitigation of voltage variation,
- Peak loading (congestion) relief,
- Reliability improvement,

The listed technical benefits can be either traded in a local service market between MS and DSO or implemented as price signals

To achieve expected technical benefits, the following are needed:

- Optimal dimensioning and allocation of Micro Sources
- Coordinated multi-unit MS dispatch based on real time grid condition

Summary of Environmental and Social Benefits of Microgrid Operation

Environmental benefits of Microgrid can be mainly attributed to:

- Shift toward renewable or low-emission fuels used by internal MS
- Adoption of more energy efficient technologies such as CHP

Social benefits of Microgrid can be summarised as:

- Raise public awareness and foster incentive for energy saving and GHG emission reduction
- Creation of new research and job opportunities
- Electrification of remote or underdeveloped areas

8.4 Retrospect and Action Recommendations

Essential benefits of Microgrids:

1. Maximum substantiation of locality and selectivity value of MS penetration
2. Over-The-Grid trading: consumer choice, MS units get quasi-retail price
3. Dissemination of MS (esp. RES) benefit to consumer side, demand side motivation
4. DSO initiative via interest sharing in local markets and supply quality improvement
5. Easier identification of potential technical improvements (U, I) and service items
6. Transparent platform for interest allocation, loss allocation, and emission allocation
7. Possibility of multi-objective, multi-party operation optimization
8. Minimize social burden of MS subsidization due to MS local retail profitability
9. Reduce infrastructure dependency on HV & MV grids for energy supply (reliability)
10. Potential capability of >90% self sufficiency to hedge against price volatility

Critical influence factors:

1. MS penetration level decides the maximum transferrable benefit to MS/load/DSO
2. MS controllability—full to partial (CHP) to none (RES)—decides selectivity benefit
3. MS allocation effectiveness decides max technical benefit in terms of locality value
4. National electricity price level and price volatility decides Microgrid profitability
5. Acknowledgement of local consumption opens Microgrid opportunity
6. Real time pricing allows market entry for more MS technologies with higher costs
7. Reduction of grid charge and emission tax adds to Microgrid appeal for all parties
8. Proper Microgrid operation strategy can achieve best trade-off for all objectives
9. A fair income/cost allocation scheme ensures reasonable benefits for all players
10. Political support and public receptiveness can be crucial for Microgrid adoption

Recommendations for Policy Makers:

1. Provide institutional or regulatory support for allowance of 'Prosumer' type of aggregators with both supply and demand side resources (i.e. Microgrid in financial sense)
2. Forbid overlaying TSO and DSO from collecting grid charges for energy flows within a Microgrid as if the same amount of electricity is imported in traditional manner.
3. Emission or emission-related taxes (if applicable) on end consumers in a Microgrid should be levied for the part of energy that is supplied from local RES resources.

Recommendations for Regulators:

1. Impose separate metering of generation and load as a compulsory measure to all applicable nodes of a Microgrid so as to maximize system transparency and facilitate technology-based financial support for expensive MS units
2. Allow differentiated handling of market-based MS units that depend on local retail market for basic profitability and subsidized MS units that need to be remunerated by special tariffs that consist of external financial supports on top of local sales.
3. Introduce protection schemes to the confidentiality of internal trading prices within a Microgrid so as to avoid potential abuse of market power.

Recommendations for DSO that hosts one or more Microgrid(s):

1. Whenever possible, negotiate with each MS owner in terms of unit dimensioning and interconnection location (if applicable) to maximize extractable benefit and minimize the possibility of MS-caused network problems.
2. Limit initial MS connection charge to costs associated directly with installation and interconnection (shallow charge), and apply ensuing operation related charges and remunerations (when MS provides a recognized technical service) to each MS unit on a real time basis according to its instantaneous impact on grid performance.
3. Avoid looking at MS (LV) and DG (MV) units simply as a threat to potential UoS revenue, the forgone part of grid charge could be potentially offset by interest sharing in local retail market and extra revenues created by improved service quality.

Recommendations for Microgrid operators:

1. Make day-ahead and real time dispatch decisions based on grid constraints, targeted performance levels, emission cost reflections, and internal market bidding results.

2. When DSI and/or storage measures are applicable for daily operation, apply all demand-side dispatches before committing MS units so as to avoid market confusion.

3. Try to avoid allocating Microgrid revenues solely to one player under free market setting, trading settlements are best performed on real-time basis.

Recommendations for MS owners/operators:

1. Select MS technology based not simply on investment and basic running costs, but also includes consideration of geographical, meteorological and logistical applicability as well as financial support policies (if applicable).

2. When choose to rely on retail and wholesale price gap for basic profitability, check historical retail price levels and tariff components as well as national trends to ensure sufficient future FLH so as to speed up return of sunken investment.

3. Negotiate with DSO to identify each and every potential opportunities of service provision or grid charge reduction as early as planning stage, it may be too late to look at these possibilities after initial interconnection.

Recommendations for end consumers:

1. Consider real-time or time-of-use pricing programs as cost-saving opportunities rather than definitive extra spending causes: if changing your consumption habit could lead to lower energy tariffs while doing everything in old fashion leads to higher costs, then why not just change your habit?

2. Even if do not directly own or operate MS units that 'invade' your private territory (such as PV panels on your roof) or cause slight inconveniences to your life (such as the front-door wind turbine blocking the view from your window), consider them as extra opportunities for reducing your electricity bill and reducing your carbon footprint in the same time.

3. One day you might find three types of power outlets in your home labelled in order of 'crucial', 'schedulable', and 'interruptible' with decreasing electricity tariffs. Do not panic—connect your computer to the first one, your wash machine to the second one, and your fridge to the third one, then relax and enjoy your life as usual.

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Technical Annex

Annex 1 **Stochastic Modelling of RES, CHP, and Electricity Markets**

Annex 2 **Node-to-Link Load Flow Method and Its Application to Optimum Power Flow (OPF)**

Annex 3 **Microgrid Scheduling via Genetic Algorithm and Heuristic Search**

Annex 4 **Reliability Impact of DER and Microgrids on Low Voltage Grids**

Annex 5 **Report on Technical, Economic and Environmental Benefits of Microgrids on Power System Operation - Study performed by *INESC***

Annex 6 **Report on Economic Benefits of Microgrids - Study performed by *NTUA***

Annex 7 **SOCIAL BENEFITS OF Microgrids – Study performed by *UKIM* and *ICEIM-MANU***