Advanced Architectures and
Control Concepts for

MORE MICROGRIDS

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WPH. Impact on the Development of Electricity Infrastructure

TH1. Modelling of microgrid evolution and replacement profiles of EU network infrastructure

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Executive Summary

The overall aim of Work Package H is to quantify the impact of a widespread deployment of Microgrids (MG) on the future replacement and investment strategies of the EU network infrastructures. Within the WPH general framework, the specific objectives of *Task TH1. Modelling of microgrid evolution and replacement profiles of EU network infrastructure* were to develop:

- A microgrid evolution roadmap for the years 2010, 2020 and 2030;
- Electricity demand and supply scenarios;
- Transmission and distribution grid infrastructure replacement scenarios.

The aim of this report is thus to illustrate the investigations carried out within Task TH1, based on which a number of assessment analyses will be run in Task TH2 and Task TH3. In the sequel, the directions that have been followed to address and achieve the above objectives are outlined.

Microgrid evolution roadmap and future demand/supply scenarios

In order to formulate an evolution roadmap and future demand and supply scenarios, extensive investigations have been carried out in the attempt to gather relevant data from the partners. In this respect, a general approach for assessing microgrid benefits with specific focus on network aspects has been formulated, and the schemes needed for data collection and modelling purposes within the generic network models developed in WPH have been identified. Hence, relevant data have been collected from selected countries (namely, Germany, UK, Netherlands, Poland, and Macedonia) for the analyses to be carried out through the generic distribution system (GDS) model developed within this work package, aimed at assessing the impact of microgrid operation in current networks. The process of data collection has been carried out in collaboration with Task TG1 Further relevant information provided has been used for scenario development besides network assessment. In particular, useful general information on electricity demand and supply scenarios and network infrastructure in EU from 2010 to 2030 has been extracted from the data provided by the partners for the scenario modelling discussed below.

Data collection itself has not proven sufficient for developing sound infrastructure evolution scenarios. Hence, further investigations have been carried out to identify the major features relevant to current power systems and to the major drivers for the shift towards decentralized energy systems. Hence, the role and the benefits of MG within the current framework and potential future scenarios have been highlighted for the different sectors composing the power system (generation, transmission, distribution, demand).

From the general analysis it has emerged how the major drivers for microgrid development in current scenarios are related to efficiency increase within multiple energy sectors and environmental impact reduction, besides possibility of deferring infrastructure investment and improving the reliability of electricity supply. In particular, the main

features of the most widespread microgeneration technologies such as photovoltaic (PV) and cogeneration (CHP – combined heat and power) systems have been discussed, pointing out the systems in which their benefits could be highest. On the other hand, in the future benefits are most likely to be related to contributing to increase the power system flexibility.

Indeed, in order to cope with climate change and draw energy paths more sustainable for the future generations, a number of challenging goals have been set out by government in Europe and worldwide. In particular, large-scale technologies based on renewable energy sources (RES), mostly wind, are envisaged to be widely deployed in the future, with nuclear power potentially coming back *in auge* as well. In addition, carbon capture and storage (CCS) systems are being intensively investigated with the aim of developing cleaner thermal generation. However, the operation of RES, nuclear and CCS-equipped plants might all imply additional challenge for the energy system operation. In fact, RES such as wind or solar power are to a large extent unpredictable and uncontrollable, while current nuclear and potential CCS systems should be typically operated in base-load for economic and technical reasons. Hence, major issues in terms of flexibility could arise with the penetration increase of such technologies, as the cost of keeping in operation flexible thermal power plants only to provide regulation and reserve balancing services might skyrocket. The option of shedding considerable amount of wind power to maintain frequency stability in the case of blowing wind does not appear sound either.

In such a future energy scenario dominated by large-scale central generation systems, the widespread presence of distributed small-scale systems is not conflicting. Indeed, major benefits from microgrids will be related to the possibility of dispatching controllable loads and local generators to cope with all the possible uncertainties from large-scale operation of inflexible and uncontrollable resources.

Controllability does not appear to be a big issue at this stage of limited penetration of DG. However, if a fit-and-forget approach is applied, the potential benefits from DG integration will not turn up. On the other hand, MG in the future will not only facilitate a wider integration of large-scale clean energy sources, but will also contribute to design and operate distribution networks as well as transmission networks in a more economical and efficient way by enabling to control the power flow from the "bottom" level of the classical hierarchical structure.

In addition, it is envisaged that local generation of power, cogeneration of heat, and in case tri-generation of heating, cooling and power, will allow an enhanced *development of integrated energy systems* that also take into account the presence of other energy vectors such as gas and in perspective hydrogen. At the same time, the possibility of shifting loads for heating/cooling generation with thermal storage, electrical vehicle recharging, and so on, will allow further increase of the efficiency and economics of the overall energy sector operated in an integrated fashion.

On the basis of the information gathered and of the general analyses carried out, a demand/supply framework scenario (Table ES.1) and a microgrid evolution roadmap

(Table ES.2) relevant to the next two decades have been formulated for Europe, including technologies and role of microgrids within the foreseen evolving frameworks.

As a key point, the roadmap and the scenarios developed take into account the increasingly important position of electricity as an energy vector relevant to other energy sectors, such as heating/cooling generation and transportation (electrical vehicles). Hence, in an electricity-dominated energy system, the role of MG to manage growing loads with various characteristics (unpredictability, intermittency, and so on) besides relatively inflexible centralized generation is highlighted further. However, at the same time distributed generators and loads controlled within microgrids allow the development of economic and efficient integrated energy systems that connect distributed multi-generation plants.

Table ES.1 Evolution scenarios developed for Microgrids and power systems.

		2010	**2020**	**2030**
DG penetration in microgrids		10%	20%	30%
CHP/PV share in EU regions	***North***	95/5%	90/10%	85/15%
	Central	60/40%	55/45%	50/50%
	South	20/80%	25/75%	30/70%
Conventional generation flexibility		medium/high	medium	medium/low
Average CO_2 emission factor variation		0	-20%	-50%
Load variation	***low***	0	+10%	+20%
	BAU	0	+30%	+50%
	high	0	+50%	+100%

Infrastructure replacement scenarios

Within the highly complex evolution scenarios described, modelling of replacement profiles of EU network infrastructure has been a daunting task. Indeed, power system operators often do not have enough information to address this issue beyond a short-term time window, and when they have it, such information is often precious and not to be disclosed. Therefore, starting from the general network information gathered, we have developed a number of methodologies and tools to model and assess the evolution of generic transmission, distribution and generation infrastructure.

In particular, besides the GDS model mentioned above, a statistical distribution network model based on fractal theory has been developed to generate, design and simulate representative distribution networks with MG. The fractal tool enables to generate large multi-voltage networks with characteristics that can be tuned, and can thus be used to simulate networks with given features resembling specific networks in Europe on a system-wise basis. Hence, by generating generic network with typical characteristics, it is possible to identify optimal design strategies and capture the benefits provided by microgrids in large realistic networks that yet are not related to any specific case study application. A minimum life cycle cost approach has been adopted to model the network replacement scenarios, which is consistent with the data provided by partners indicating the trend towards design stronger networks as from the optimal design approach followed. By evaluating the cost of network design for different penetration levels of DG, different technology mix, and different control strategies, the impact of MG on distribution networks and the additional value provided can thus be identified. As an illustrative example, Figure ES.1 below shows the network value of uncontrolled micro-cogeneration systems in a generic 33/11/0.4 kV urban distribution network in the UK serving 150,000 consumers.

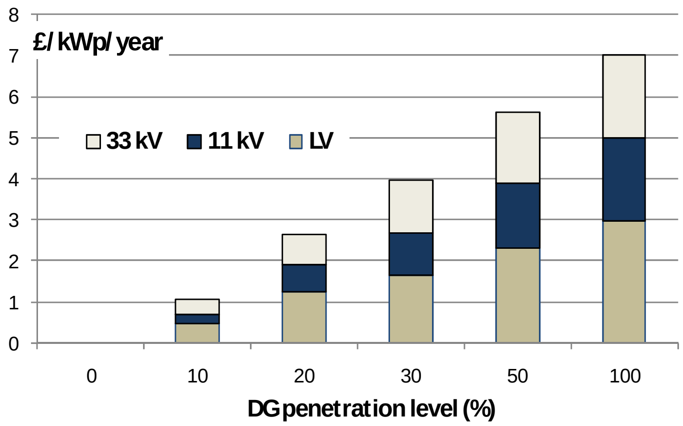

Figure ES.1. Value of microgrids with uncontrolled micro-cogenerators in a generic UK urban network, with breakdown of the avoided cost per voltage level.

An approach similar to the generic distribution system model has been taken up to model the replacement scenarios for transmission networks, outlining a cost-benefit methodology for transmission system development that takes into account the optimal level of trade-off between investment costs and congestion costs. The model developed also enables to address the interaction of MG with centralized generation through a static first-approximation approach that is able to provide valuable information to assess the environmental performance of the overall power system. In addition, a dynamic approach to model the interaction between centralized generation and MG has been discussed to highlight the role of MG in terms of increasing flexibility in future energy systems.

In addition to the objectives specifically set out within Task TH1, a number of methodologies and models have been introduced to assess the environmental impact from operation and design of infrastructure in the presence of MG. More specifically, starting from an energy chain model aimed at illustrating the primary energy saving and emission reduction that can be obtained through distributed energy systems and, as a particularly relevant sub-case, cogeneration, the environmental assessment has led to the identification of the concept of external costs. External cost analysis allows internalization of environmental aspects within the economic models used for network design, so that an optimal comprehensive network assessment can be carried out.

Relevant numerical applications to networks in different European countries, based on the data collected and deploying the models and the methodology developed in this task, will be analysed in Task TH2 and Task TH3.

Table ES.2. Microgrid evolution roadmap.

<table>
<tr><th></th><th><2010</th><th>2010</th><th>2015</th><th>2020</th><th>2025</th><th>2030</th><th>>2030</th></tr>
<tr><th>Stage</th><th>Infancy</th><th colspan="3">Development</th><th colspan="2">Maturity</th><th>Full integration</th></tr>
<tr><td rowspan="2">Equipment</td><td>Current limited level of DG at LV: micro-CHP, MT, PV</td><td colspan="2">Additional DG penetration at LV in hot spots, mostly driven by economic reasons (CHP, in case backed by incentives);
regulatory back-up for RES (PV, mainly)</td><td>Electrical vehicles become widespread</td><td></td><td colspan="2">After replacement deferral, infrastructure to be replaced (aging, RES penetration, etc.);
distribution systems based on MG/Multi-MG</td></tr>
<tr><td></td><td colspan="3">CHP with heating and cooling networks (MV); trigeneration;
small-scale wind (LV, MV);
small-scale hydro (LV, MV);
controllable loads for heating/cooling</td><td></td><td></td><td></td></tr>
<tr><td rowspan="2">Market</td><td></td><td colspan="3">Market interaction with upstream grid and centralized generation;
DG aggregation and market interface</td><td></td><td></td><td></td></tr>
<tr><td></td><td></td><td colspan="4">Market model enhancement through VPP;
controllable DG, DSM, AM in MG;
multi-microgrids interacting with each other and with external markets through VPPs;
interaction with transmission system</td><td></td></tr>
<tr><td rowspan="2">Infrastructure Impact/Role</td><td></td><td colspan="4">DG/RES increase calls for requirements for generation and load local centralized controllability through smart metering, DSM, active management;
microgrids internal markets for resource dispatch; impact <u>on</u> centralized generation scenarios -> conventional generation (thermal, large RES) changes (higher efficiency, peaking plants, old plants displaced, etc.)</td><td></td><td></td></tr>
<tr><td></td><td></td><td colspan="4">Impact of centralized generation scenarios on benefits brought by MG (energy, emission, losses, security, to be rethought in part);
“updated” role of MG -> major driver: controllable MG as a key tool to manage large RES penetration and more inflexible mix with nuclear and CCS; microgrid “active” role increasing with the years, with the need for a more active network (DSM and AM), rather than for “spot benefits”; MG are operated and designed together with other infrastructures relevant to other energy vectors; integrated energy systems and distributed multi-generation</td><td></td></tr>
<tr><td>Research</td><td>Studies on drivers for change</td><td colspan="2">System-wise impact analyses for network (losses, infrastructure deferral, reliability, etc.) and for energy, environmental and economic benefits</td><td></td><td colspan="3">New distribution system design: optimal circuit design including DG, DSM, AM, and so on;
conventional generation has changed; transmission system to be reconsidered with RES, CCS and MG; CBA analysis</td></tr>
</table>

Contents

ACRONYM LIST

AM	Active Management
BAU	Business As Usual
CBA	Cost-Benefit Analysis
CCGT	Combined Cycle Gas Turbine
CCS	Carbon Capture and Storage
CHP	Combined Heat and Power
CO2ER	CO_2 Emission Reduction
DCHP	Domestic or Distributed CHP
DG	Distributed Generator
DH	District Heating
DNO	Distribution Network Operator
DSM	Demand Side Management
DSO	Distribution System Operator
ESP	Electrical Separate Production
FC	Fuel Cell
FESR	Fuel Energy Savings Ratio
F&F	Fit-and-Forget approach (or passive management – PM – approach)
FL	Fault Level (short circuit capacity)
GDS	Generic Distribution System
GSP	Grid Supply Point
GT	Gas Turbine
HV	High Voltage
ICE	Internal Combustion Engine
ICT	Information and Communication Technology
LCA	Life Cycle Assessment
LCC	Life Cycle Cost
LHV	Lower Heating Value
LV	Low Voltage
MG	Microgrids
MX	Mixed (cables/lines)
MT	Microturbine
MV	Medium Voltage
OH	Overhead (lines)
PE	Primary Energy
PER	Primary Energy Rate
PM	Passive Management
PV	Photovoltaic
PW	Present Worth
RES	Renewable Energy Sources
SP	Separate Production
TSO	Transmission System Operator
TSP	Thermal Separate Production
UG	Under-Ground (cables)
VPP	Virtual Power Plant

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1. Introduction

EU transmission and distribution networks were significantly expanded in the late 50's and early 60's. The assets then installed are thus approaching the end of their useful life and will soon need to be replaced. This opens up the opportunity to reconsider the fundamentals of distribution system design and operation in the light of the most recent technological developments. At the same time, the evolution of power systems in the last years is witnessing manifold changes, *in primis* due to the arising of new challenges related to define more sustainable energy paths for a growing population. Hence, the uncertainties intrinsic in the development of any type of scenarios, being they for generation, demand, network design, etc., is so high that foreseeing even short term trends might become a daunting task. Formulation of network replacement scenarios, in particular, is a major challenge due to the unpredictability of a number of factors ranging from energy prices to renewable support policies. Thus, network operators and more generally actors operating in the power system sector have no clear-cut picture of what the next energy future will look like.

In spite of the uncertainties in the energy system evolution, undoubtedly distributed generation (DG) is changing the focus from only large centralized power systems hierarchically operated towards including also local energy systems with decentralized control. The major drivers for this are economic and environmental efficiency of renewable energy sources (RES) or high-efficiency thermal generation (for instance adopting cogeneration) for distributed applications, besides network benefits.
While no major issues have arisen hitherto regarding DG integration, mostly seen as negative demand in distribution networks, increasing penetration levels as is envisaged in a number of countries will make it necessary to identify new strategies for grid integration. In addition, new issues will come up with the shift towards more decarbonised energy systems based on intermittent renewable sources such as wind, inflexible generation such as most of current nuclear plants, or future thermal plants equipped with carbon capture and storage (CCS), as well as with the growing amount of loads for electricity-based heating/cooling generation or transportation. Hence, while on the one hand more and more large-scale low-carbon generation systems are planned to be installed in the future, on the other hand distributed energy systems might represent an enabling factor to overtake specific problems that might arise in terms of flexibility, network congestions, and so on.

Microgrids (MG) applied to low voltage (LV) networks have proven to be able to provide enhanced reliability services and a number of benefits ranging from technical to economic one. However, no adequate studies have been carried out to address the implications of widespread deployment of MG within current and future power system infrastructure on a system-wise basis. Thus, if on the one hand MG will contribute to change the "classical" structure of electric power supply towards more decentralized solutions, on the other hand the role and the impact of MG in a more than ever evolving scenario needs to be adequately addressed yet. In particular, micro-generation integrated in the form of MG could play a key role in reducing the expenditure associated with alternative network replacement strategies. Similarly, controllable loads and demand side management (DSM) strategies within MG will contribute to mitigate the downsides brought about by increasing loads and supply/demand balancing issues due to more intermittent generation and load types.

On the above concepts, Work Package H (WPH) of the *MORE MICROGRID* Project aims at quantifying the impact and the benefits of a widespread deployment of MG on the future replacement and investment strategies of the EU network infrastructures. In addition, the environmental implications of such strategies will also be assessed, given the rising criticality of environmental issues, particularly with respect to climate change. This takes also into account the impact of MG on centralized large-scale generation and its likely evolution.

Within the general framework of WPH, this report summarizes the activities carried out with reference to Task *TH1 – Modelling of microgrid evolution and replacement profiles of EU network infrastructure*. In particular, formulation of generic models of electricity infrastructure with MG and comprehensive approaches for the relevant analyses are presented. More details on the numerical results for different countries are provided in Deliverable DH1 and Deliverable DH2.

As discussed above, scenario development at this stage of multiple forces contributing to change the energy sector is not easy to carry out. On top of everything, Microgrids look at the power system evolution in the long term, so that scenarios are even more challenging to develop. Hence, in this work we have developed sound methodologies to study the impact of MG on current networks and then to model the power system evolution in the presence of MG and of a number of concurring variables. The primary aim is to highlight the key variables involved in developing large MG-based energy systems, and thus to help network operators and policy makers take strategic decisions in setting out the lines for a sustainable power system development.

In order to assess the ability of Microgrids to displace network assets and to quantify the network-related value of MG, specific representative models of transmission and distribution networks and relevant simulation tools have been developed. These tools are based on detailed load flow and voltage profile calculations, necessary to analyse the effects of widespread Microgrids on the network assets that were originally designed in top-down hierarchical structure. Apart from analysing potential scenarios as they can be foreseen for specific countries, it has to be underlined that the tools developed are flexible enough to enable sensitivity studies to be carried out to examine the impact of a number of key factors on the overall benefits that MG can bring at a system-wise level. In particular, different micro generation technologies, levels of penetration, levels of integration of micro generation within MG, seasonal operating patterns, correlation with (growing) demand, and network design approaches can be accounted for. On the basis of the results provided by the tools developed, specific methodologies have then been formulated to quantify the overall benefits that MG can bring in typical EU electricity systems, including investment savings, loss reduction, improvement in the operation economics, increase in energy efficiency, and environmental benefits at regional, national, and European levels.

To tune the parameters of the models developed, as well as to input realistic data for European electricity infrastructure, relevant information has been collected within Task TH1 about the present and future EU scenarios regarding generation, demand and network infrastructures. Data collection has been carried out in coordination with Siemens for Task TG1. Specific data have been provided by selected partners according to the Generis Distribution System (GDS) model template developed by Imperial.

As a major output from this task, data collection together with suitable assumptions (above all when data were not available) and modelling approach have enabled us to formulate a *Microgrid evolution roadmap* in EU, regardless of the relevant intrinsic uncertainties. In particular, three future Microgrid scenarios, also related to the level of penetration of microgeneration for years 2010, 2020 and 2030. The technology deployment scenarios mainly refer to micro-CHP and PV systems, being the most widespread in Europe. In addition, electricity demand and supply scenarios (from 2010 to 2030) have been modelled and developed on the basis of the collected data and/or assumptions in order to determine the system context for MG scenario assessment.

The report is organized as follows:

- Chapter 2 presents a general introduction on current power systems and the major drivers for the shift towards decentralized energy systems. Then, the role and the benefits of microgrids within the current scenario and potential future scenarios are discussed for the different sectors composing the power system (generation, transmission, distribution, demand). In particular, it is highlighted how while the benefits in current scenarios are likely to be related to efficiency increase and environmental impact reduction, in the future the primary role of microgrids could be more related to improve system flexibility, with major benefits brought by controllability of loads and local generation. The main features of the most widespread microgenerators such as photovoltaic and cogeneration systems are also discussed, pointing out the systems in which their benefits could be highest.

- Chapter 3 introduces the schemes needed for data collection and modelling purposes within the generic network models developed in WPH. The general approach for microgrid benefit assessment within distribution networks is also illustrated.

- Chapter 4 presents the issues, methodologies and tools developed for transmission, distribution and generation infrastructure assessment. In particular, the generic distribution system (GDS) model, the fractal distribution model, and the cost-benefit analysis (CBA)-based transmission system model are illustrated, discussing their main features and potential use, and highlighting some issues related to generation controllability in microgrids. In addition, the interaction of microgrids with centralized generation is also discussed through a static and a dynamic approach, with this latter useful to point out the role of microgrids in increasing flexibility in future energy systems.

- Chapter 5 introduces a number of methodologies relevant to environmental impact assessment and that post-process the results from the network assessment models. In particular, an energy chain model is presented with the aim to capture the benefits of decentralized energy systems in terms of energy saving and security of supply, as well as of emission reduction, with respect to classical centralized systems. In addition, also the local environmental impact due to distributed energy systems is discussed, eventually leading to the general concept of energy externality (environmental cost) to be applied to both global emissions (mainly greenhouse gases) and pollutant local emissions. The external cost framework enables to extend the economic assessment of microgrid-integrated network infrastructures to environmental aspects as well, paving the way to a comprehensive multi-criteria evaluation of costs and benefits of microgrids. Finally, given the importance of cogeneration in decentralized energy systems, specific models for energy saving and emission reduction relative to conventional separate production of electricity and heat are also presented and exemplified.

- Chapter 6 provides an overview of the data identification process carried out together with WPG for microgrid assessment and scenario development.

- Chapter 7 presents a synthesis of the data collected for identifying suitable supply and demand scenarios in Europe. Further data are provided in Annex 2 and in Deliverable DG1.

- Chapter 8 presents the methodology and the generic multi-voltage network model developed for modeling replacement scenarios. In particular, after describing the general features of the tool developed, based on a fractal approach, it is highlighted how the model flexibility enables to generate generic networks and simulate generic conditions, allowing to study the impact of microgrids scenarios on large generic network scenarios and thus on a system-wise basis. An illustrative case study exemplifies the methodology developed to assess the value of microgrids on network design.

- Chapter 9 sums up the main findings from data collection, investigations and model development in this Task by drawing a microgrid evolution roadmap in Europe relevant to the next two decades. More specifically, after discussing the interaction features between future microgrids and power systems and the major future drivers for benefits, microgrid evolution scenarios are illustrated according to a number of criteria, including technologies and role of microgrids within the foreseen evolving frameworks. As a key point, the roadmap developed takes into account the increasingly important position of electricity as an energy vector relevant to other energy sectors, such as heating/cooling generation and transportation (electrical vehicles). Hence, in an electricity-dominated energy system, the role of microgrids to manage growing loads with various characteristics (unpredictability, intermittency, and so on) besides relatively inflexible centralized generation is highlighted further.

- Chapter 10 contains the concluding remarks of the work performed in this Task.

- Annex 1 presents the main part of the templates used for data collection relevant to GDS analyses.

- Annex 2 reports a number of load and generation profiles and scenarios provided by selected partners for some of the analyses to be performed in the next tasks. Further relevant data that have been collected are contained in the Deliverables in WPG.

2. Overview on conventional network models and benefits from a decentralized microgrid paradigm

After illustrating the typical characteristics in the major number of current power systems designed for unidirectional power flows from centralized generation to final users, this Chapter summarizes the fundamental drivers and enabling factors prompting the evolution towards more decentralized energy systems. In particular, aspects such as infrastructure replacement and generation and network efficiency according to environmental and economic criteria are highlighted, also in the light of potential changes relevant to sectors complementary to the electrical one, such as heating generation and transportation. Within such an evolving framework in the overall energy field, it is then discussed the primarily role that microgrids could play, at first to increase network and generation environmental and economic efficiency, and then to contribute substantially to increase the power system flexibility in generation scenarios dominated by uncontrolled or inflexible low carbon sources.

2.1 Typical features of classical power system

Implementation of innovative MG will shift the power system operation and design philosophy from a *traditional* centralized energy system towards a decentralized one.
In order to capture the benefits that microgrids could bring, the first step is to outline the main characteristics of conventional power systems. Although of course the specific characteristics may vary from country to country, the overall "centralized" rationale lying behind the current power system implementation can be considered commonly shared around Europe.
The classical physical power system structure is divided into four main blocks, namely:

- generation,
- bulk transmission,
- distribution, and
- utilization/demand,

and is schematized in Figure 2.1. In particular, two major aspects can be appreciated in the traditional design and operation of power systems:

1. *flows* are typically *unidirectional*, from large power plants through electricity transportation networks to the final users;
2. *passive management* (PM) of distribution networks and no active role played by the demand.

Both these major aspects together with other ones will be detailed in the sequel in order to point out the differences relative to the microgrid-based paradigm.

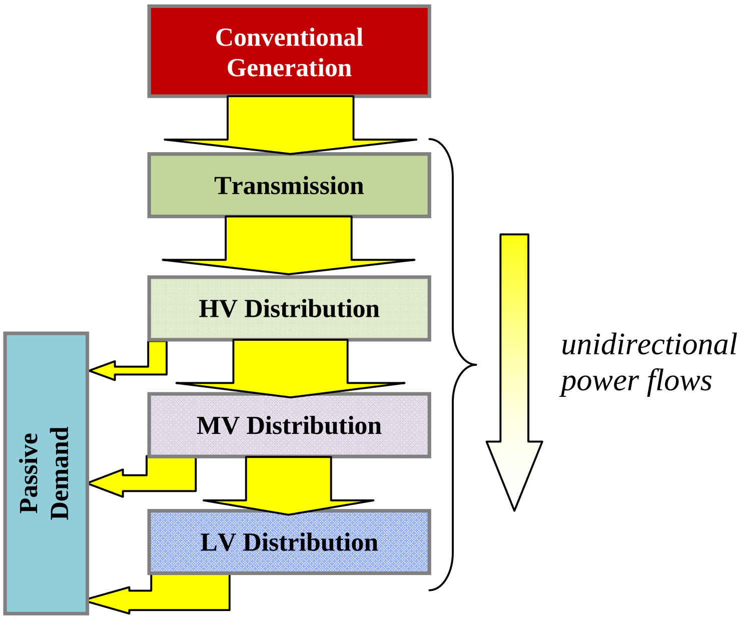


Figure 2.1. Schematic model of energy flows in conventional power systems.

2.1.1 Generation

Current power systems in most countries are characterized by large centralized power plants (above 100 MW to few thousand of MW). The demand is typically characterized by uncontrollability for most of users, changes on a seasonal and daily level, and is partially unpredictable. Power curtailment is mostly not allowed, whereas power interruptions may be extremely expensive. In addition, a certain power reserve margin (for instance against sudden plant faults) must always be guaranteed. Hence, power systems are typically designed with "peaking" features, even though the average load is quite low. For instance, in the UK the capacity utilisation level is of the order of 55% [1]. Another key point common to most power systems in Europe is the presence of extensive fossil fuel-based generation. The efficiency of the state-of-the-art technologies (large modern Combined Cycle Gas Turbines - CCGTs) is comprised between 55% and 60%. However, the average efficiency is in general quite lower (of the order of 40% in the UK, for instance), due to coal and oil based steam cycles, as well as older gas turbine systems, whose efficiency may be below 30%. Hence, large amounts of heat discarded from the thermodynamic cycles are wasted away through cooling towers or water-cooled condensers utilizing river, lake, or sea water.

2.1.2 Transmission

Given their importance in terms of system security and economics, electrical transmission networks are usually designed with large capacity redundancy enabling the network to keep in operation even after outages of circuits, according to at least an *n-1* security criterion. Hence, transmission circuits are normally operated far from their thermal limits. However, network topology and market situations can bring up several issues at the transmission level. For instance, the UK transmission network witness major southbound power flows from North (where the main generation is situated) towards South East (where the main consumption hub, driven by London, is situated). As a consequence, flow congestions may arise, which are dealt with by constraining off northern generators with lower marginal costs than southern ones, thus increasing the overall operational cost with respect to an idealized (network-free) market-based dispatch. Due to the geographical configuration and generation siting, similar southbound flows occur also in Italy, for instance, and network congestions are commonplace in most countries. In a competitive environment, costs of congestion should be managed in the long term by appropriate investment in network capacity [1]. However, besides economic aspects, the presence of corridors of limited capacity and major flows along the transmission system might represent a potential threaten to security, with very serious consequences.

2.1.3 Distribution

Most EU networks were designed or redesigned after World War II. Consequently, the aged asset is reaching to its useful life end. In addition, although distribution networks were typically designed with large capacity margin, the growing (sometimes skyrocketing) demand is often rendering the remaining margins before reaching thermal or voltage limits very shallow. Hence, also in the light of the need to increase the energy efficiency and decrease the carbon burden from energy generation, distribution network control, design, operation, and investment strategies need to be rethought.
In terms of losses and power quality, the distribution level usually represents the core of the overall network. For instance, in the UK annual losses in distribution networks are about 7%, whereas about 90% of the customer interruptions are related to the two lowest voltage levels, namely, 11kV and 400V. Such reliability figures primarily depend on the radial design of these networks, so that any fault on a circuit leads to downstream supply interruptions.

2.1.4 Demand

Demand in current systems is characterized by large *uncontrollability* and extensive temporal effects, in terms of daily and seasonal variations. For instance, in the UK the minimum demand occurs in summer nights and is about 30% of the winter peak. Apparently, increasing the overall load factor would bring benefits to the "peaking" operation of the system. That's why in several countries there are growing incentives towards making demand more "responsive".
In addition, it emerges how diversity in usage of appliances represents a key aspect of demand. For instance, typically the capacity of an electricity system supplying several thousand households would be only about 10% of the total capacity that would be required if each individual household were to be self sufficient (individually supplied by its own generation, Figure 2.2). Hence, balancing electrical demand and supply at the

household level may be inefficient in both terms of design (larger capacity is needed) and operation (generators would be continuously cycling up and down and on and off), as the low-pass filter effect due to network aggregation of several users is lost.

2.2 Drivers for change towards decentralized energy systems

On the basis of the issues discussed above, it can be summarized that the main features of current power systems depend on the fact that centralized generation in large power plants occurs far from the relatively distributed demand hubs, so as to make it necessary to have an extensive network connection. Building up on these premises, it is possible to highlight some of the main drivers that justify the latest trends of shifting towards decentralized energy systems. More specifically:

- **Climate change**. For most European countries the challenges brought by the need for tackling climate change are representing the major drivers towards adopting decentralized energy systems, with the possibility of integrating zero-emission renewable energy sources (RES) available *in situ* as well as high-efficiency cogeneration systems.
- **Energy efficiency.** Carbon emission reduction is closely related to energy efficiency increase. This can be seen both in terms of generation technology (for instance, cogeneration systems), as well as in terms of networks and generation/demand interaction. From the latter point of view, DG systems could also contribute to decrease consistently the losses in the network, and thus to increase the overall system efficiency.
- **Security of supply.** For fuel based systems, higher efficiency means lower fuel consumption per unit of output (electricity and heat, in case). This in turn means increase of security of supply, which is another major issue in today’s rapidly changing political and economic worldwide scenario. DG technologies through different forms of generation are thus an important resource not only in terms of higher efficiency, but also in terms of enhanced fuel diversity. Similarly deployment of RES locally available would further contribute to diversity and security of supply.
- **Security, reliability, and power quality**. The general philosophy behind decentralized energy systems lies in the principle that closing up generation and demand would contribute to increase quality of service and the level of security with respect to a centralised structure, besides efficiency and environmental benefits. Indeed, in distributed power systems faults, congestions, voltage drops, and so on, could be more easily tackled through availability of multiple generators connected close to the users.
- **Need for asset replacement or reinforcement.** In several countries network replacement strategy will soon need to be implemented due to asset aging. For instance, in the UK a significant proportion of the network is expected to have to be replaced within the next two decades. More in general, network replacement or reinforcement can be necessary for various reasons, such as for instance higher-than-expected load growth. Availability of distributed energy systems might contribute substantially to determine new network planning strategies, in which

the new assets (to be operated for the successive decades) is optimally designed and operated according to specific objective functions (for instance, minimum life cycle economic cost). In alternative, it could also be the case that, thanks to a distributed architecture, the current assets are optimally exploited and their update is postponed by even several years.

- **Information and communication technologies** (ICT). ICT are playing an increasingly important role within the power system sector. This is due, in particular, to the need for operating the system in a more efficient way. The diffusion of decentralize energy systems will be backed up by hi-tech ICT, and, in turn, their efficiency can be highly improved by suitable ICT platforms, for instance through real time measurements that allow for active management of the network.

2.3 Role of microgrids and relevant issues related to their deployment in current and future power system

2.3.1 General issues

From the above discussions, it emerges how there is a number of drivers leading to a shift towards decentralized energy systems.
The main point to be raised is that DG technologies may typically experience wide variations in output because of their dependency on the natural variability of the energy resource (for RES) or on heat demand (for heat-driven Combined Heat and Power – CHP). This is a key difference relative to conventional technologies that mainly operate at or near their full power output with just limited variability caused by maintenance and unplanned outages. Since operators of RES generators have no control over environmental conditions, their power output generators vary according to the wind strength, solar irradiation, water flow speed, etc., or in the case of heat-driven CHP (and in the absence of heat storage), according to the heat demand. As the primary energy resource or the heat demand fluctuates, so does the power output of a DG system too.
The instantaneous gap between generation and consumption, which occurs in a relatively unpredictable manner, is balanced through the network. With currently small number of buildings equipped with micro-CHP (also indicated as DCHP – Distributed or Domestic CHP) and DG units producing small amounts of electricity, their impact on power system is negligible. However, if the share of buildings with generating systems becomes far larger, than the effect on the grid may become significant, and further planning and operational actions need to be undertaken.
The microgrid paradigm lies within this overall DG framework, as special applications of distributed energy systems with distributed generation technologies. However, there are some specific attributes and issues relevant to microgrids that make them a key protagonist among the possible distributed paradigm for a more secure, efficient and sustainable future energy supply. In particular, the network impact of MG will depend on their penetration level as well as on the interaction patterns between generation and demand. From this standpoint, this interaction can be somehow accommodated through

actions aimed at increasing the *controllability* of MG, which can also mitigate possible negative effects due to DG variability.
Some of these issues are described in this section and then detailed in the sequel of this work.

2.3.2 Generation

Cogeneration (CHP) systems

Cogeneration systems (and in particular micro-CHP as a special case) are likely to play a major role within the microgrid framework. In fact, according to what discussed above in this Chapter, the overall energy generation efficiency could be consistently increased if it was possible to exploit the discarded heat for low temperature uses. It is important to highlight that demand for low-grade heat (space heating and hot water) represents a consistent quota of the overall energy demand in western countries. For instance, low-temperature heat demand represents some 25% of the entire UK energy demand. In spite of the fact that new building standards have the potential to reduce substantially the space heating demand, it is unlikely that such demand will decrease in the future and could indeed even increase while looking for higher comfort conditions. Heat discharged from fossil-fired power plants could be exploited if potential thermal users relatively close to the generation point were at disposal. Indeed, in general it might be neither economical nor efficient to transport large quantities of heat generated in large power plants over long distances, with potentially high heat transportation energy losses, as well as high investment costs due to long heat transmission systems.
Implementation of microgrids adopting micro-scale (below 100 kWe) or small-scale (below 5÷10 MWe) CHP systems within rural or urban areas would allow the exploitation of the discarded heat to supply space heating and hot water demand from local users. This could occur at:

- Household level (micro-generators typically in the range 1÷5 kWe);
- Dwelling building level (for instance, microturbines (MTs), currently in the range 30÷250 kWe);
- Commercial/tertiary building level (for instance, Internal Combustion Engines (ICEs) with capacities of the order of 1 MWe, for office buildings, commercial mall, hospitals, sport centres, and so on);
- District level. In this case, several houses/buildings could be aggregated together through *heat networks* (District Heating – DH) coupled to the electrical microgrid, with capacities and feasibility depending on several factors, but in principle possible in the range 30 kWe (few consumers) up to few MWe, for which utilization natural gas ICE or Gas Turbines (GTs) can be envisaged.

Although electrical efficiency of relatively smaller units is in general lower than for large power plants, utilization of rejected heat in cogeneration raises the overall fuel utilization efficiency up to 80%-90%. In addition, distributed technology improvement is such that electrical efficiency of small units is becoming increasingly higher. This applies for instance to modern ICEs of sizes of the order of 1 MWe, whose typical electrical efficiency range is around 40%, thus even higher than for simple cycle GTs or steam turbine plants. A further point in favour of decentralized generation is represented by the possibility of exploiting cogenerated heat to fire thermally-activated technologies for cooling generation. This would help relieving the electrical peaks occurring in several Southern countries in the summertime due to the increasing demand for electric air conditioning.

Micro-CHP units are typically used in domestic applications (DCHP) with size ranges between 1 and 5 kWe, and are normally connected at LV. The main difference of DCHP systems relative to large-scale CHP ones is in the priority of generation. Large-scale CHP systems mainly generate electricity with heat as a by-product, or however can modulate their load typically taking into account economic issues such as energy prices and so on. On the contrary, micro-CHP systems, which operate at individual buildings and do not typically face time-differentiated prices, are driven by heat demand, with electricity being a by-product. Because of its heat-driven operational behaviour and since the electricity demand of individual homes fluctuates much, these micro-CHP systems often generate more electricity than is instantly being consumed in the building, injecting the exceeding part into the grid. As detailed in this work, the presence of a positive correlation between generation and loads is one of the main drivers to bring positive network benefits.

Owing to the higher fuel utilization efficiency, CHP systems can bring consistent primary energy saving and carbon emission reduction, which currently represents major challenges in most EU countries, in the attempt to cope with security of supply issues and to tackle Kyoto's Protocols commitments. Specific models quantifying the extent to which CHP systems operating in MG can bring primary energy saving and CO_2 emission reduction are illustrated in Section 5.5.

In spite of a high overall efficiency, and thus potentially primary energy saving and carbon emission reduction, CHP economic profitability is typically a non-linear function of the energy prices, and might be hindered by low buy-back rates for the electricity sold to the grid because in excess to the users' demand. From this standpoint, implementation of microgrids with "private wiring", or anyway where the electricity produced in cogeneration can be allocated to specific distributed local users (rather than sold back to the DSO) at a profitable rate, could boost the adoption of CHP systems, thus enhancing both energy efficiency and economic efficiency of the energy system. High carbon prices would also increase the attractiveness of CHP systems. These issues are further dealt with in Tasks TH3.

Renewable Energy Sources

Micro-RES such as wind or PV systems exhibit both spatial and temporal variability on different time scales. In addition, other renewable systems such as hydro-based are typically limited to the sites with large availability of natural resources (Macedonia, for instance).
The main upsides of RES are their characteristics of "fuel" cost-free as well as emission-free. Hence, RES deployment within MG could bring substantial environmental benefits

to the overall power system owing to displacement of fossil fuel-based centralized power stations. Of course, the extent to which PV, mini-hydro and micro-wind can have a significant (positive) impact on the generation and thus overall energy infrastructure system depends on the specific Country considered, with its available resources and demand characteristics.

In terms of generation characteristics, micro-RES typically exhibit short-term production fluctuations due to changes in environmental conditions, such as clouds, rainfall, strong wind gusts, and so on. In addition, for PV systems variations in solar radiation occur on diurnal and seasonal basis. For wind turbines, very short-term fluctuations are typically partially absorbed by mechanical parts. For PV cells, instead, there is no such inertia, as primary energy resource is directly transformed into electricity and the characteristic time constant of electric devices is negligible. However, for system assessments it is reasonable to assume that short-term fluctuations are reduced by aggregating geographically distributed units. Hence, when no detailed data are available for different locations, average information from aggregated systems can be utilized in the analyses.

As hinted above for DCHP, also for RES the correlation between generation and demand is highly significant not only for replacing energy, but also for replacing capacity [3], which impact directly on (generation and network) system cost. For instance, in Northern countries CHP systems are expected to bring benefits in terms of displaced energy as well as capacity, since the production occurs mostly at peak hours, in the wintertime. On the other hand, PV might not have any capacity value as it cannot displace peak generation in these countries. Differently, PV could be the key technology in Southern countries with peak demand occurring in the summertime (due to air conditioning utilization), when PV produces the most. Nevertheless, it has to be pointed out that air conditioning applications are fast increasing in number even in relatively colder countries (in UK, for instance), so that a peak shift towards summertime might occur in the future. In this case, PV solutions should not be ruled out a priori in terms of their potential capacity credit.

The capability of displacing generation capacity has a manifold impact (including network issues), namely, from energy, environmental, losses, network capacity, and economic perspectives. Relevant models and analyses in this sense will be detailed below and further investigated in Deliverable DH2 and Deliverable DH3.

2.3.3 Transmission

As discussed in Section 2.1.2, power flow control at the transmission level is carried out primarily through generation dispatching, and possible congestions would cause generation cost increase (to be sorted out, on the long run, with transmission capacity investment).
Distributed energy systems with microgrids could contribute to decrease possible congestion levels (for instance due to major unidirectional flows in limited capacity corridors), as well as to increase the overall system security and reliability by shifting the generation closer to the demand. Indeed, a power system with widespread penetration of

MG would be characterized by *regional hubs* where energy is generated and consumed mostly locally and exchanged at the distribution level, while the use of the transmission grid would be mainly related to make up for possible unbalances among regions. Of course, this would be true only to a certain extent, as there might be in any case the need for exploiting the transmission system for instance to transport power generated in large off-shore wind farms or hydro-systems, whose siting is determined by the physical location of natural resources.

On the above premises, in general transmission capacity upgrade investment for congestion reduction could be put off or avoided through distributed generation in microgrids. In addition, decentralizing (at least in part) the energy generation would contribute to decrease the risk associated to major flows through a limited number of corridors, increasing the overall system security. As a further point, although annual energy losses in transmission systems are lesser than in distribution network (for instance, in the UK are below 2%), MG avoiding transmission flows would decrease the associated losses again increasing the overall power system efficiency.
Specific models have been developed in WPH to quantify the value of microgrids relevant to transmission investment saving (Section 4.4). Relevant numerical analyses are provided in Deliverable DH2.

2.3.4 Distribution

Distribution networks have been traditionally designed to be operated with *no real-time control* besides network reconfiguration. In other words, currently the control problem of distribution networks is sorted out at the planning stage (*passive* networks or *passive management*). The introduction of DG in distribution networks, in particular in the form of MG, brings about a series of issues and could unveil several benefits.

First of all, microgrids at the distribution level would mean localized generation close to the load centres, avoiding power flows through the distribution networks (and the transmission network) from centralized generation. An immediate consequence of microgrid implementation is related to loss reduction, due to the avoided power flows in the lines.
In addition, strategic investment in distribution network, for instance needed for capacity enhancement due to increasing demand, could be postponed thanks to local production. While the previous aspect is in general more relevant for urban networks, excessive voltage drop problems that might arise above all in rural areas might also be avoided through MG and DG, owing to an adequate voltage support effect.

Nevertheless, the opposite problem (voltage rise) might show up as well in the presence of electrical generation uncorrelated to the demand, so that adequate impact analysis and network planning must be carried out. Voltage rise or loss increase problems might occur for instance due to uncontrolled DG systems such as PV or micro-wind whose production is uncorrelated to the load. CHP systems can be considered uncontrolled too, to some extent. This applies above all for domestic CHP, generally operated under heat-tracking mode, being electricity-only generation operation not efficient (average electrical efficiencies at a micro-scale are of the order of 10÷20%) and the presence of heat dumping devices representing a further economic burden. Storage systems to decouple electrical and thermal generation could be a solution, but at a household level would require the adoption of suitable controllers.

In the case of asset aging, microgrids implementation could represent a temporal solution to keep on with the current asset before new investments are carried out. Indeed, new distribution assets would stay in place for decades, so it is crucial, for DNOs and the entire community, that suitable design strategies are analysed, taking into account the updated environmental and security of supply issues, as well as the presence of growing DG itself. This is to avoid that not adequately designed networks (including too early replacements) might lead to set up an inefficient network to be in operation for decades. On the other hand, replacement strategies entailing DG and MG will exhibit characteristics well different from the current cases with no or little microgeneration, and need to be properly addressed. As a last point, although not an objective of WPH, it is important to underline that MG can consistently increase the quality of supply, for instance by serving the users even in radial networks after an upstream fault occurred.

A key aspect in distribution network including microgrids will be represented by the possibility of modifying the characteristics of the network and of the connected agents (customers and generators) in order to fully exploit the potential of the asset. In other words, this would lead to set up an *active* distribution network able to promptly respond through *active management* (AM) and Demand Side Management (DSM) strategies to the variable generation/demand configurations that might take place, with both operational and design benefits. In particular, a positive correlation between load and generation is one of the main drivers for benefits in microgrid systems, but unfortunately this is not always the case. In addition, reinforcement costs might be necessary due to DG penetration, for instance because of fault level (FL) increase in urban areas. Such costs could be reduced through appropriate active network management strategies, helping cope with the situations that would otherwise hinder the possibility of widely exploiting DG and its benefits. On the other hand, provided that DG diffusion in distribution networks is likely to increase in any case, maintaining the traditional passive operation , together with centralised control at the transmission level, could lead to capacity increase in both transmission and distribution networks. A practical example is already occurring in Denmark, with a highly distributed energy system based on CHP, and for which there is a need to move from the classical *fit-and-forget* (F&F) approach towards actively integrating generation (beyond a "negative load" modelling) and network operation and design.

The general models developed here to analyse impact and benefits of MG with different DG typologies (PV, CHP, etc.) on the distribution networks are described in Section 4.2 and Section 4.3.
Relevant analyses, with also application to typical EU country situations and scenarios, are then presented in Deliverable DH2. The lack of recognition of potential benefits

brought by microgrids, which could adversely impact on the competitiveness of decentralized systems, will also be discussed in Deliverable DH3.

2.3.5 Demand

As mentioned in Section 2.1.4, balancing electrical demand and supply at the household level may be and often is inefficient. However, aggregation of several users within MG (and, a special case, operating in islanded mode) could resemble the same load diversity benefits as the ones occurring through distribution networks. Of course, this raises the issue about the minimum number of users needed in order to appreciate load diversity effects. In this respect, Figure 2.2 illustrates how the *simultaneity factor* (ratio of network peak demand to user average peak demand) changes with the number of typical households in the UK. With already 100 households it is possible to get an average network peak five times lower than for the single user, while 1000 users would make this average peak drop to ten times lower. However, it can also be appreciated how moving further in terms of user aggregation would not bring significant contribution. In general, the presence of diverse load typologies such as offices, commercial, schools, and even small industrial users, with load characteristics in part complimentary to the ones from residential users, would decrease the number of users for which load diversity becomes significant. Hence, MG with some few hundreds of users (as usually served by one or few more MV/LV substations) could already benefit from consistent load diversity peak reduction, which could be particularly significant in the search for match between local generation and loads.

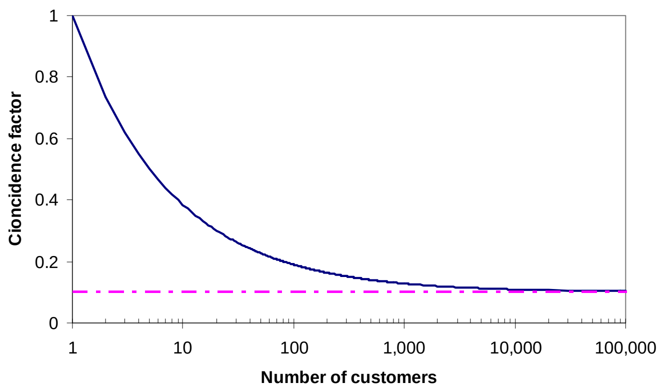


Figure 2.2. Load coincidence factor vs. the number of typical households.

A key aspect for the development of decentralized and in general more sustainable energy systems is the need for a more *responsive demand*, in case through the application of demand side management (DSM) strategies and potentially storage systems, which is also connected to AM options for DG operation. From this standpoint, user within microgrids would/should play a more *active* role, either in terms of responsive loads (somehow, with demand “following the generation” in order not to create unbalances or constrain inefficient operation alternatives), or even in terms of producers (for instance, DCHP). Hence, the overall effect would be to make user more aware of and participative to challenges such as security of supply and global warming, possibly further increasing the system overall operation efficiency. Application of more sophisticated energy meters is of course a crucial enabling factor to implement DSM options.

The above issues are all related to the concept of microgrid *controllability*, according to which possible negative impacts on the network and insufficient economic performance might be mitigated by adoption of opportune corrective strategies related to simultaneous AM and DSM. Thus, microgrids able to optimally dispatch controllable loads besides local generators pursuing given objective function such as peak flow or emissions minimization might represent a precious asset to enable power systems to be operated more flexibly and efficiently. Further aspects in this light are discussed in Section 4.5 with reference to the role of MG of increasing the power system flexibility for balancing purposes in the presence of large uncontrollable or inflexible low-carbon generation, and in Section 9.1.3 relevant to system evolution perspectives.

3. General framework for distribution network identification and evaluation in the presence of microgrids

This Chapter discusses the general framework developed to identify distribution networks in different EU countries and to assess the impact of microgrids on current assets. More specifically, metrics such as overall losses reduction for different voltage levels, overall avoided CO_2 emissions from more efficient network utilization, network reinforcement investment deferral, and energy produced locally and displacing centralized generation are defined for various penetration levels of microgeneration. In addition, in order to carry out the microgrid impact assessment the basic data to be provided by the partners, ranging from network characteristics to generation and demand scenarios, are identified, discussed and exemplified.

3.1 Overview of microgrid characteristics and benefits to be assessed in WPH

The challenge of developing a new energy system paradigm with decentralized power systems and large deployment of DG and micro-generation is related on the one hand to the potential benefits, and on the other hand to the additional costs and issues that such paradigm will bring up.
In this outlook, suitable models and tools are needed to run all those evaluations that help clearly establish all the upsides and downsides of microgrid implementation. In particular, development of new networks with MG and micro-generation could be suitably addressed by coping at a design stage with the potential technical issues that might arise. On the other hand, integration of microgrids within existing networks could represent a scenario even more challenging. Such would for instance be a scenario with high penetration of domestic DG systems (e.g., micro-CHP, micro-wind, or PV) within current low voltage networks (that would be transformed in MG) that are not designed for bi-directional power flows.

Among the main issues to be addressed, power injection from micro-generation in LV networks could cause voltage limits (above all in rural areas) and switchgear fault ratings (above all in rural areas) to be exceeded. At the same time, changing the traditional unidirectional flows towards the user because of local generation could impact on energy losses, while the potentially diminished flows through the network from upstream levels could postpone needs for capacity reinforcement, for instance due to load growth. The extent at which the above phenomena would occur is a complex and non-linear function of the specific network characteristics, as well as of the interaction between load and generation. Apparently, powerful and general tools are needed in order to cope with the above issues.

As the overall aim of WPH is to quantify the impact of a widespread deployment of MG on the future replacement and investment strategies of the EU network infrastructures, representative models and suitable evaluation methodologies and tools have been developed. More specifically, the methodologies and the models developed, as well as the analyses run, are relevant to:

- Impact of microgrids on network energy losses;
- Impact of microgrids on network investment deferral;
- Environmental impact of microgrids;
- Economic assessment of microgrids.

The general approach to tackle issues more closely related to distribution network assessment is illustrated in this chapter. The relevant methodologies and tools developed are illustrated in Chapter 4. The environmental impact models developed, which are based on the results from the network assessment models, are then presented in Chapter 5. Further discussion and numerical applications, also including economic analyses for all the considered issues, are reported in Deliverables DH2 and DH3 of WPH, as well as in the analyses run in WPG.

3.2 General network assessment framework

3.2.1 Main objectives of the assessment framework

In order to be able to evaluate technical, economical and environmental benefits that may result from the presence of micro-generation in the electrical grids, a general assessment framework has been developed by INESC Porto with the following objectives:

- identify overall energy loss reduction in all network voltage levels (distribution and transmission) at a regional and national level;
- identify the overall avoided CO_2 emissions that result from the avoided active losses in the electrical networks;
- evaluate the investment deferral in network reinforcements, by identifying the number of years that corresponds to postponing investments;
- evaluate the annual energy that can be produced locally at the micro-generation level.

The development of this approach requires a first step where typical (generic) distribution networks must be identified. In order to obtain a European evaluation of the benefits described previously, the utilities involved in the project should provide data on typical, representative, distribution networks for their countries, considering the typical voltage levels (HV, MV, and LV) and present and future operational scenarios of microgeneration penetration (including different generation technologies) and load growth patterns.
Further details on the approach formulated are given below in this Chapter. The models and the methodologies developed by Imperial are then outlined in the following chapters. A significant amount of data has been collected in collaboration with WPG to support the analyses run. Some of these data are reported in Chapter 7 and in Annex 2, whereas the bulk of them are provided within the outputs from WPG.

3.2.2 General approach

The distribution network evaluation methodology in the presence of MG has been divided into three simple steps and is presented next.

1. Data identification/acquisition for each country

- Definition of typical distribution networks for each voltage level (HV, MV and LV);
- Definition of operating scenarios considering estimated load profiles for each of the networks;
- Definition of micro-generation penetration levels, according to the generation technology available, for each of the networks (considering integration levels and typical operational patterns for each type of micro-generation technology, i.e. PV micro-generators operating only at day time, micro-CHP operating only when people are at the households, etc.).

2. Network Prototyping

- Prototyping typical Northern and Southern European distribution networks, by taking into account mainly load profiles and micro-generation technologies. This information will be used for generalisation purposes, namely, when no national specific data is available. On the basis of the network prototypes, it is envisaged to carry out:
    - Analysis of each network prior to the integration of micro-generation;
    - Analysis of each network after the integration of micro-generation.

3. Analysis Procedure

- Quantification of the overall benefits due to wide microgrid diffusion, mainly focusing on four objectives, exploiting results from the previous steps:
    - Loss reduction;
    - Environmental benefits;
    - Investment deferral;
    - Evaluation of the overall amount of energy produced at the load level.

3.2.3 Data identification

Typical networks

Each utility should identify typical grids for each country at the distribution level, concerning all distribution voltage levels, namely, HV, MV, and LV networks.
Apart from the distribution network data, data from the transmission network should also be gathered, in order to evaluate technical and economical benefits that will appear at this level. This includes information related to typical load levels and generation profiles that

may occur during a one-year period of operation, in order to take into account the seasonal effects.
For each of the distribution networks, an example of the basic data that should be provided is presented in Table 3.1.

Table 3.1. Data Request Form.

Each utility should provide data on typical networks for LV, MV and HV levels in order to fully characterize the network, including namely: - One-line diagram; - Base voltage; - Line and/or cable data: branch resistance, reactance and susceptance, line/cable length, nominal rating, status; - Transformer data (HV/MV and MV/LV): leakage reactance/short-circuit impedance, rated power, transformer ratio, status. Each utility should provide data on the load profiles at each bus for each of the networks. Each utility should provide data on foreseen micro-generation penetration concerning different generation technologies, namely: - Micro-CHP generation; - Mini-hydro generation; - PV generation; - Micro-wind generation, etc.

Regarding LV and MV typical networks, at least two networks types should be identified corresponding to typical urban and rural areas.
Concerning the HV network, the identification of one typical grid model should be sufficient.
For illustration purposes, Figure 3.1 shows the one-line diagram of a typical urban MV network for Portugal. It is a 15 kV network, with a meshed structure and highly reconfigurable, with an injector node at bus NO95. Figure 3.2 presents the one-line diagram of a typical urban LV network for Portugal (400 V).
Note that all networks concerning the case-study in Portugal, including all data on base voltage, line parameters, load and generation profiles, are presented within Work Package G.

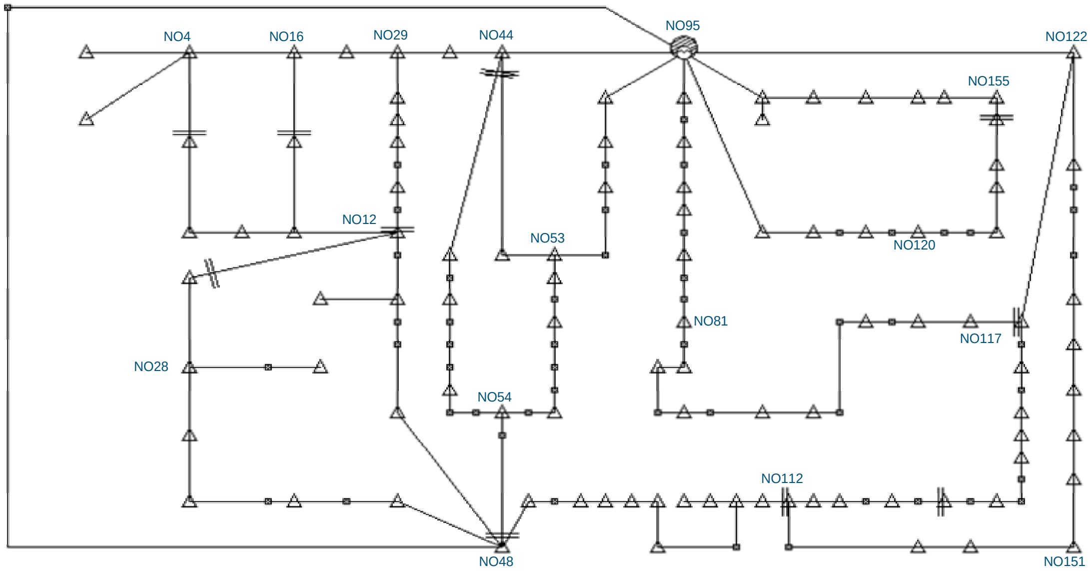


Figure 3.1. Typical urban distribution MV network for Portugal.

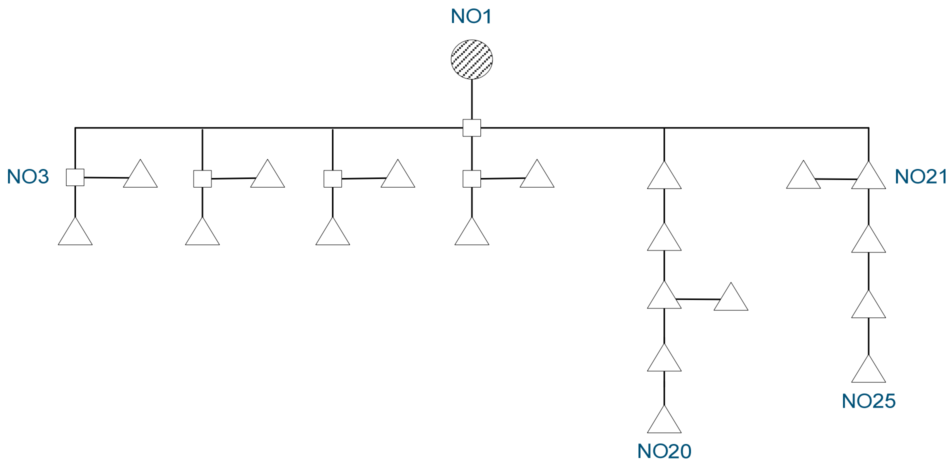


Figure 3.2. Typical urban distribution LV network for Portugal.

Load scenarios

For each of the networks, the peak load at each node for a given time span (typically concerning a recent one year period) should be obtained. The sum of all load values will reflect a "simultaneous peak load". This simultaneous peak load is obviously unrealistic, as the peak in each node will not occur at the same time. Hence, a reduction will be applied through a "*simultaneity factor*" that will be described ahead.
In order to build the load scenarios, consumer load curves concerning a 24-hour period must be identified and provided. These load diagrams can be typically divided into three different types, according to the type of network considered:

- Residential consumers;
- Commercial consumers;
- Industrial consumers.

A load curve resulting from the combination of these three load diagrams must also be derived, and shall be expressed as a percentage of the simultaneous peak load value.
In addition to daily load variations, seasonality must also be considered. Thus, the simultaneity factor referred to earlier should be established for at least winter and summer scenarios, in order to affect the simultaneous peak load, for each of the networks.
For illustration purposes, Figure 3.3 presents an aggregated (considering residential and commercial consumers) typical load diagram for Portugal. The simultaneity factor considered is 0.8 for winter and 0.7 for summer (because in winter time there is typically higher load than in summer, despite the growing use of air-conditioning devices in Portugal).

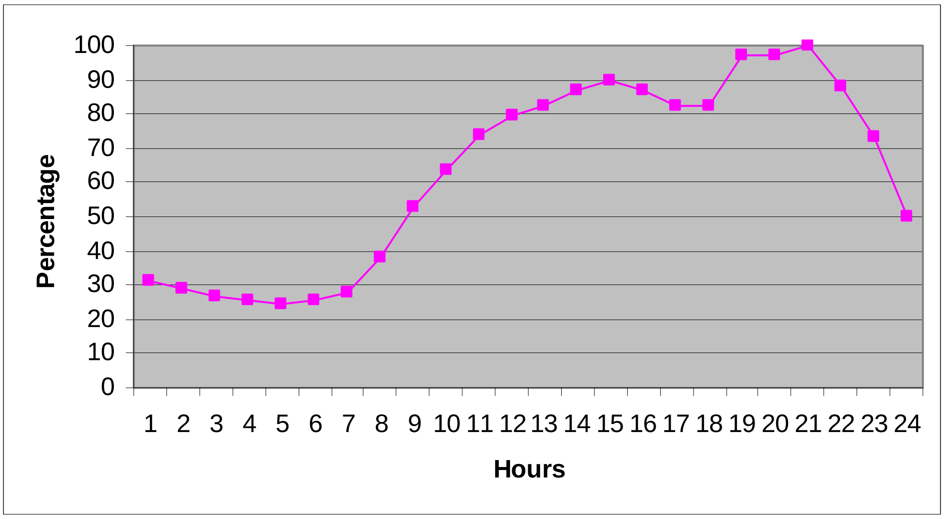


Figure 3.3. Typical aggregated daily load diagram for Portugal (% of peak value).

The above load profile is assumed to be the same at all LV load buses.

Generation scenarios

Future generation scenarios must be developed concerning the micro-generation technologies most likely to appear in each network. The technologies should reflect the type of network they are included in; for instance, CHP will be concentrated mainly in urban areas.
For each type of network and each load profile, different micro-generation penetration scenarios will be developed considering different types of generation technology, namely:

- Micro-CHP generation;
- Mini-hydro generation;
- PV generation;
- Micro-wind generation.

Nevertheless, other technologies may be considered, according to what is expected to be developed for each typical network.
Several situations should be explored, namely considering that the percentage of micro-generation penetration can, for instance, account for 0% (base case) 10%, 20% and 30% of the total simultaneous peak load of each network. Hence, by running such parametric analyses and regardless of the actual scenario forecast, the impact of microgrids and their suitability to be deployed in specific networks can be analysed.
Consequently, for this approach, a micro-generation penetration index can be defined as:

$$\mu G_{penetration} = 100 \cdot \left(\frac{\sum P_{nom}^{\mu G}}{P_{load}^{peak}} \right) \tag{3.1}$$

where:

- $\mu G_{penetration}$ is the micro-generation penetration (expressed in %);
- $\sum P_{nom}^{\mu G}$ is the sum of the installed capacities of all micro-generators connected in a LV network for a given scenario;
- P_{load}^{peak} is the total peak load for a given scenario.

Daily generation diagram profiles, for each season, must be identified and be available for each of the micro-generation technologies. This information is quite relevant since PV generation levels can be considerably high during a large period of the year in the southern European countries while they can be much smaller in the northern European countries. On the other hand, CHP contribution can be quite relevant in northern European countries, especially during wintertime, while CHP micro-generation levels can be smaller in southern European countries.

It must be stressed that the main aim of this analysis is to evaluate the impact of micro-generation in the MG. Consequently, only the impact of micro-generation penetration at LV should be considered, with no DG to be connected directly to the MV and HV level.

Some other initial assumptions include:

- The LV networks connected to the MV level are all considered to be microgrids;
- A given percentage for each type of networks should be defined initially for each country to be analysed. For instance, for Portugal 60% of the MV networks connected to the HV level are considered to be of the urban type and 40% are considered to be rural type.

The inclusion of micro-generation is simulated by reducing the load at all load nodes according to the load reduction at each node covered by micro-generation, which

involves tackling properly with micro-generation contribution across the daily load diagram.
A scenario is defined for each network and each season (for instance, winter and summer), considering typical load and generation profiles.
In order to calculate the load reduction due to the inclusion of micro-generation, the following formula was applied to all LV and MV buses, for a single typical day of each scenario, and for each of the 24 hours:

$$P_{load}^{red} = p_{MG} \cdot \sum_{i=1}^{4} \left(P_{i,h}^{MG} \cdot p_i \right) \qquad (3.2)$$

where:

- P_{load}^{red} is the active power load reduction due to the inclusion of micro-generation;
- p_{MG} is the percentage of micro-generation penetration (0%, 10%, 20% or 30%);
- i is the micro-generation technology (1 – CHP, 2 – Hydro, 3 – PV, 4 – Wind);
- $P_{i,h}^{MG}$ is the active power provided by the micro-generation technology i at the hour h, according to the available generation profile;
- p_i is the percentage of the contribution of the generation technology i.

Although the extension of this micro-generation penetration to the MV loads may be questionable, such an assumption is an attempt to include the fact that a considerable amount of MV loads (large commercial and service buildings, apartment buildings and small industries) would join the micro-generation formula in their installations.

For the HV distribution network, the same formula is used twice to determine a weighted average, considering, that *X*% of the MV networks connected to the HV level are urban and *Y*% are rural ($X + Y = 100\%$). These percentages can be parameterized according to the system under analysis. As mentioned above, for the Portuguese study case it was assumed that 60% of these MV networks are of urban type, being the remaining 40% of the rural type.
At the HV distribution level it is also important to consider that a percentage of the HV loads can be of the industrial type, without the presence of any local generation. In order to cope with this issue, a few load buses can be randomly considered as “only load type”, assuming that such labelling is defined after a uniform distribution (for the number of buses in the HV grid). In this way only a certain number of load buses are considered as connected to MV grids that have a given micro-generation participation, as previously defined. For illustration purposes the percentage for each generation technology (p_i) for each distribution network is presented below, considering the study case defined for Portugal.

Table 3.2. Generation percentages for each scenario per technology (Portugal case).

Network	Generation Technology	Percentage per Technology
HV	CHP	42,00%
	Hydro	16,00%
	PV	26,00%
	Wind	16,00%
RMV	CHP	
	Hydro	40,00%
	PV	20,00%
	Wind	40,00%
UMV	CHP	70,00%
	Hydro	
	PV	30,00%
	Wind	
RLV	CHP	
	Hydro	40,00%
	PV	20,00%
	Wind	40,00%
ULV	CHP	70,00%
	Hydro	
	PV	30,00%
	Wind	

Note that these percentages were estimated taking into account not only the expected future scenarios for generation for Portugal but also the different technologies available for each type of network. Each country should develop a similar table concerning the specificities of the generation technologies available.

Concerning each micro-generation technology, also a typical daily generation diagram for each technology and for each season must be developed and expressed as a percentage of its installed capacity.

For illustration purposes, Figure 3.4 presents the typical generation diagram for a micro-PV micro-generator in winter time for Portugal and Figure 3.5 shows the typical generation diagram for a micro-PV microgenerator in summer time for Portugal. Figure 3.6 presents the typical generation diagram for a micro-CHP installation for Portugal (considered equal for winter and summer time).

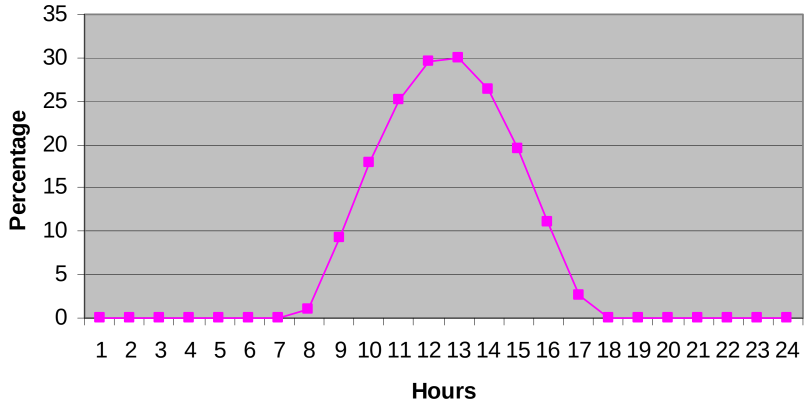


Figure 3.4. Typical Daily micro-PV Generation Diagram for winter in Portugal (% of installed capacity).

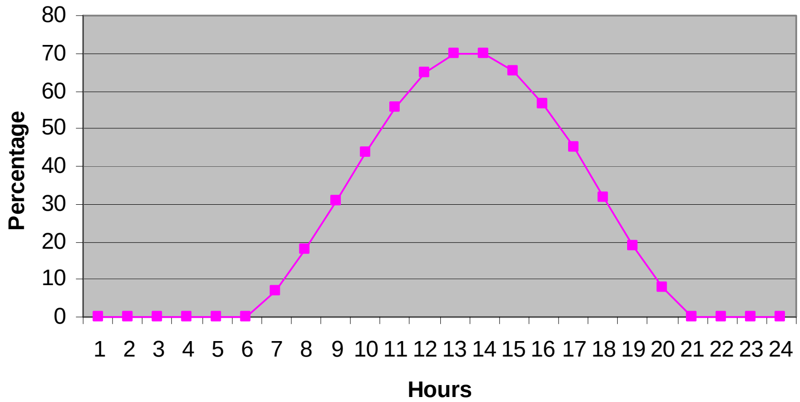


Figure 3.5. Typical Daily micro-PV Generation Diagram for summer in Portugal (% of installed capacity).

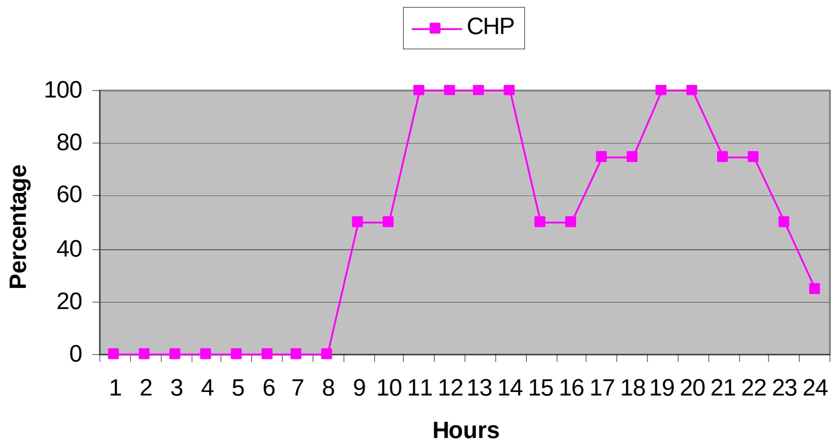


Figure 3.6. Typical Daily micro-CHP Generation Diagram in Portugal (% of installed capacity).

Network prototyping

In the case there is no national specific data available, and for generalisation purposes, an approach based on prototyping typical northern and southern European networks may also be envisaged.
This approach should rely mainly on the identification of a typical grid structure, as well as of the micro-generation technologies available for each particular case in order to develop a model network for southern and northern Europe.

Analysis procedure

The typical networks identified in the previous sections will be analysed in order to allow the quantification of the overall benefits due to microgrid diffusion. The evaluation of these benefits will be made according to three distinct objectives, as it has been seen previously:

- Loss reduction;
- Environmental benefits, namely reduction of CO_2 emissions;
- Investment deferral;
- Amount of energy produced at load level.

In order to be able to analyze the impact of micro-generation penetration in distribution networks, a power flow tool should be used to simulate each network considering all possible mixes of both load and generation scenarios.
For simulation purposes, the integration of micro-generation is considered as a load reduction at each node where the micro-generator is supposed to be connected to.

Loss reduction

Loss reduction due to the inclusion of micro-generation can be quantified by considering an average energy cost (€/kWh). This cost is estimated to be 0.0524 €/kWh for Portugal and should be estimated for each country.
The total losses should be calculated by using the difference between the losses obtained considering the different micro-generation penetration levels (10%, 20% or 30%) and the losses without micro-generation.
The percentage of annual energy losses reduction for each network should be estimated for a one-year period. This value is obtained considering the daily power losses for at least a typical winter day and a typical summer day (and for instance assuming that 50% of the year is winter and 50% is summer).
Then, in order to quantify in terms of cost the percentage of energy loss reduction for each network, one must multiply the average cost for the kWh of losses, the percentage of annual energy losses reduction for each network and the annual energy losses:

$$C_{Eloss} = C_0^{avg} \cdot p_{loss}^{red} \cdot E_{loss} \tag{3.3}$$

where:

- C_{Eloss} is the cost of the energy loss reduction;
- C_0^{avg} is the average cost for energy;
- p_{loss}^{red} is the percentage of annual energy losses reduction;
- E_{loss} is the annual energy losses for the network under analysis.

The next step will be to obtain a global estimate of the economical benefits resulting from the loss reduction due to the inclusion of micro-generation. For this purpose an identification of the distribution of losses in the different networks considered for this analysis should be available for each country and for a recent year. Then, the total energy losses in distribution systems will be distributed by the different types of networks: HV, MV rural and urban and LV rural and urban. Table 3.3 presents, for illustration purposes, the percentages that indicate the allocation of energy losses according to the type of network for the case of Portugal (normally this information can be obtained from Regulating authorities and/or from distribution utilities).

Table 3.3. Distribution network percentage concerning energy losses per voltage level.

Distribution Networks	Percentage of the Total (%)
Rural LV	24
Urban LV	36
Rural MV	8.84
Urban MV	13.26
HV	3.9

The estimation of these percentages was based on the following assumptions:

- of the whole distribution system, 60% of the networks are LV and 40% are MV and HV networks;
- of the MV and LV networks, 40% are rural networks and 60% are urban networks;
- of the 40% MV and HV, 85% correspond to MV networks and 15% to HV networks.

Using the percentages presented in Table 3.3, the global benefits of the energy losses reduction resulting from the inclusion of micro-generation can be estimated by calculating:

$$C_{Eloss}^{global} = \sum p_{loss} C_{Eloss} \tag{3.4}$$

where:

- C_{Eloss}^{global} is the global benefits of energy losses reduction;
- p_{loss} is the distribution network percentage concerning energy losses for each voltage level (as presented in Table 3.3);
- C_{Eloss} is the cost of the energy loss reduction.

Environmental benefits

Potential environmental benefits of the integration of micro-generation in distribution systems may be seen in terms of the reduction of CO_2 emissions.
The reduction in CO_2 emissions is directly related to the avoided power losses. Reducing losses, and considering that micro-generation is widely based on renewable energy sources (including high-efficiency cogeneration systems), there could be a significant amount of avoided CO_2 emissions.
In order to estimate this amount of CO_2 emissions that can be avoided, one must multiply the energy losses reduction for the value representing the amount of CO_2 produced by conventional generation in order to produce a certain amount of energy. This value differs according to the generation technology and the fuel adopted. Some typical values for the most typical fuels are presented in Table 3.4.

Table 3.4. Amount of CO_2 emissions per unit of generated energy for different fuels.

Fuel	CO_2 specific emissions (ton/GWh)
Coal	346.7
Fuel oil	275.8
Natural Gas	200.9

The Portuguese Regulator estimates the amount of CO_2 emissions that are related to each GWh produced in the Portuguese system, according to the usual mix of generation technologies. This amount is 370 CO_2ton/GWh. Such information must be available for each country under study. Then the total CO_2 emissions avoided due to avoided losses is given by:

$$Emissions_{CO_2} = E_{loss} \cdot coef \quad (3.5)$$

where:
- $Emissions_{CO_2}$ is the total CO_2 emissions avoided due to avoided losses;
- E_{loss} is the annual energy losses;
- $coef$ is the reference value for CO_2 emissions (considered 370 CO_2ton/GWh for Portugal).

Investment deferral

The investment deferral may be estimated in two different ways, depending on the type of network to analyze (urban or rural).

Investment deferral in typical urban networks
It is assessed by evaluating the reduction of *line loading* by considering the integration of micro-generation on typical urban networks. It is expected that the penetration of micro-generation will relieve line loading, ensuring that the line limits are not surpassed.
In order to evaluate it, the loading of the line that is closest to its rated power limit is compared in a scenario without micro-generation and in a scenario with micro-generation penetration (10%, 20% or 30%). Then, the number of years that each grid may exist without requiring reinforcement investments is estimated for the case considering micro-generation penetration and for the base case without micro-generation, assuming a given growth rate for the consumption.

Investment deferral in typical rural networks
In the rural case, the benefits regarding investment deferral are evaluated in terms of the *voltage drop* across a feeder. This is due to the fact that in a rural network long distance lines are more common, and voltage drop is a growing concern compared to line decongesting.
In order to do so, the buses with lowest voltage value are compared in a scenario without micro-generation and in a scenario with micro-generation penetration (10%, 20% or 30%). Then, the number of years that each grid may exist without requiring reinforcement investments is estimated for the case considering micro-generation penetration and for the base case without micro-generation, assuming a given growth rate for the consumption.

In order to quantify economically the investment deferral, the investments made by the Distribution System Operator (DSO) concerning reinforcement costs (no expansion costs included!) in lines and substations can be obtained for each type of network. The investments in new equipment refer to costs in order to increase the network capacity, following an increase in consumption of 4% per year. These costs are presented in Table 3.5 for the study case of Portugal, for illustration purposes.

Table 3.5. Investments in reinforcement for distribution networks.

Equipment	Investment (Million €)
HV/MV Substation	30.06
HV Aerial Line	25.29
HV Underground Cables	5.09
MV/MV Substation	1.15
MV Aerial Line	23.27
MV Underground Cables	12.71
Transformer Stations	8.12
LV Aerial Line	9.57
LV Underground Cables	4.04
Total	94.50

Also, for all different networks a percentage of the use made for each type of investment must be estimated in order to determine the amount of investment per type of network. These values are presented in Table 3.6 for Portugal.

Table 3.6. Percentage of investment in reinforcement for each type of network.

Equipment	HV (%)	Rural MV (%)	Urban MV (%)	Rural LV (%)	Urban LV (%)
HV/MV Substation	0	30	70	0	0
HV Aerial Line	100	0	0	0	0
HV Underground Cables	100	0	0	0	0
MV/MV Substation	0	100	0	0	0
MV Aerial Line	0	100	0	0	0
MV Underground Cables	0	0	100	0	0
Transformer Stations	Not applicable				
LV Aerial Line	0	0	0	100	0
LV Underground Cables	0	0	0	0	100

In order to estimate the total profits for the Distribution Companies, the proposed model calculates the benefits for a time span of 25 years. This model estimates the amount of savings due to energy losses throughout the period, transposed to the present day, and the benefits resulting from lowering line loading and network transformers, that lead to investment deferral.

The model is represented by the formula:

$$\sum_{i=0}^{n-1} C_0 \cdot \frac{(1+t_c)^i}{(1+t_a)^i} + \frac{I \cdot t_a}{(1+t_a)} \tag{3.6}$$

where:

- C_0 is the cost corresponding to the estimated loss reduction at year zero;
- t_a is the annual update rate (8% for Portugal);
- t_c is the annual losses growth rate (4% for Portugal);
- I is the investment on lines;
- i is the year;
- n is the total number of years.

The above model considers two different terms.

- The first term considers the savings resulting from the reduction in the average annual energy losses for a time span of 25 years, at the present time. A growth rate is also considered in order to model load growth.
- The second part reflects the avoided interests due to postponing for one year the line and transformer investments. If we include the load increase due to the growth rate for

the horizon of 25 years, the avoided interested for the analysis period can be included leading to a general formula of the type:

$$\sum_{i=1}^{n} C_0 \cdot \frac{(1+t_c)^{i-1}}{(1+t_a)^{i-1}} + \frac{I_{i-1} \cdot t_a}{(1+t_a)^{i-1}} \qquad (3.7)$$

Overall amount of energy produced at the load level

It is also necessary to calculate the energy generated locally in order to estimate the installed capacity needed to generate that amount of energy.
This will imply:

- Calculating the integral of the power in order to obtain the energy for each LV network, considering the different periods of the year (winter and summer);
- Calculating the installed capacity for each type of LV network;
- Calculating the number of LV networks: this can be done by dividing the volume of the total energy that is delivered by each LV network (information available from the Regulator or utility) by the energy delivered by each type of network (integrating the load diagram);
- Calculating the final values by multiplying power and energy by the number of networks obtained previously.

Concluding remarks on the proposed assessment framework

In this section, a methodology for assessing the global benefits resulting from micro-generation integration in the distribution grid has been presented. This methodology will allow an analysis of the impact of micro-generation in the distribution system at the local (for each country) and global (European) level.
It must also be stressed that a similar analysis for estimating the benefits at the transport grid level may also be performed.

4. Issues, methodologies and tools for infrastructure assessment

This Chapter presents the methodologies and the tools developed to address the impact of microgrids on current and future network infrastructure. More specifically, the Generic Distribution System (GDS) model aims at assessing the impact of microgeneration and active management (AM) on current networks, and makes use of the data provided by the partners according to a specific template. The distribution system statistical model allows generation of generic networks with generic characteristics, and is particularly useful for developing and assessing optimal replacement scenarios of distribution networks operated as microgrids. A cost-benefit analysis (CBA) model is discussed for transmission assessment, for which the key point is represented by the role of controllability from DG sources, pointing out how the network utilization efficiency can be improved by increasing the potential for distributed controllability in microgrids. This aspect is further explored with respect to conventional generation impact, for which a static approach and a dynamic approach are discussed. The aim is to capture the centralized generation-relevant benefits brought about by microgrids in current frameworks (above all related to environmental issues) and in future power systems (mainly related to flexibility services to support increasing penetration of large-scale uncontrollable and inflexible low-carbon generation).

4.1 Overview of the methodologies and models developed

On the basis of the general methodology for assessment of MG impact on distribution network discussed in Chapter 3, several models and tools have been developed by Imperial. In particular, the basic tools developed are:

- *Generic Distribution System (GDS) model*: this tool allows detailed simulation of microgrid impact on distribution networks (analyses of losses, voltage drops, line and transformer loading, and so forth) for both generic and specific network, including AM operation. In particular, specific analyses will be run with this tool in TH2 to assess the impact of different microgrid penetration scenarios on current networks in selected countries.
- *Distribution System Statistical Model*: owing to this tool, generic LV and MV distribution networks can be generated, with different characteristics of topology, load density and load distribution. In particular, it is possible to tune the input parameters so as to resemble realistic typical networks in Europe. The generated network can be sized according to different design strategies and taking into account the presence or not of DG at the design stage. Hence, in particular, it is possible to draw replacement scenarios of possible future networks with DG (see Chapter 8).
- *Transmission Assessment model*: as mentioned in Section 2.1.2, transmission investment in a market environment in the long run is driven by congestion prices. On these premises, an optimal transmission investment tool has been developed, in which a Cost-Benefit Analysis (CBA) approach is implemented in order to assess alternative

generation and load configurations, and, in particular, the impact of *controllable* micro-grid on potential investment deferrals and future transmission investment. At the same time, a conventional generation dispatching with equivalent generators and loads as seen at a transmission level is carried out, so that it is possible to carry out a *static* assessment of the impact of alternative microgrid scenarios over conventional generation (a more refined dynamic model is also discussed in Section4.5.2). In this tool, the impact of microgrids on transmission/generation can be modelled either in terms of equivalent load or equivalent generation as seen at the transmission system buses.

The models developed are details in this chapter, while further numerical analyses are provided in Deliverable DH2 and Deliverable DH3. The issues discussed in this chapter, and the relevant outcomes from preliminary analyses run with the models developed, are also used in the formulation of the general microgrid road-map illustrated in Chapter 9.

4.2 Generic Distribution System (GDS) model

The first tool developed for assessing microgrid and more in general DG impact on distribution networks is the so called Generic Distribution System (GDS) model.
Such tool allows the investigation of typical (generic) networks, with specified characteristics that change area by area and country by country, but that are still able to provide general results without going into detailed assessment of whole power systems. Indeed, the tool is simple enough yet capable to be used for accurate investigations involving a variety of operating conditions in order to capture the temporal and spatial impacts of DG on the network.
The input parameters of the networks analysed are tuned to fit the distribution network characteristics for the specific countries, according to the data requested and provided by the partners (see Annex 1 for the description of the template through which relevant data were requested). Then, the GDS model enables to run hourly load flow analyses (on an annual time frame and on the basis of typical seasonal characteristic days) on these distribution networks, and to provide relevant results on the impact of alternative microgrid penetration and operation scenarios (including different typologies of DG equipment involved) on losses, power flows, and voltage profiles. Thereby, sensible conclusions can be drawn on the need for network reinforcement rather than on the possibility of adopting *active management* schemes to increase the network performance and the penetration of DG. Such AM schemes range from coordinated voltage control policies to curtailment of distributed generation output, if necessary. Fault level management is also envisaged by splitting substation bus-bars to reduce fault levels.

4.2.1 GDS model description

The basic topology and design philosophy of distribution networks is common in most EU countries, with multi-voltage networks and substations with transformers between these networks. Regardless the variety of networks it is possible to encounter, all of them are characterized by a limited number of overhead line (OH) and underground (UG) cable typologies to convey power from the transmission system through the different voltage levels and eventually to end users, according to the structure of Figure 2.1. OH lines prevail for the higher voltage levels, whereas UG cables are more used in the lower voltage levels, above all in high-density urban areas. Transformers may vary in capacity and number per substation, whereas cables and lines may vary in capacity and length. Of course, the specific design in a specific area may affect resistance and reactance values (the main parameters for power flow assessment), but, to a large extent, for each country it is possible to draw generic networks that at first approximation resemble the typical ones from the various Distribution System Operators (DSOs) in that country. Such networks, in particular, are similar enough in topology and design philosophy so as to allow the adoption of a common modelling approach on a Grid Supply Point (GSP) basis. For instance, in all DSOs' GSPs in the UK electrical power flows through a number of well-defined system levels that operate according to standard voltage levels, the most common of which are 132/33/11/0.4 kV. Typical voltage levels in EU can be identified according to the procedure described in Section 3.2.3, and are shown in Table 7.1.

The networks analysed in the GDS tool are operated radially, which is the typical approach in most countries. However, some networks might be operated in (weakly) meshed configuration. Meshed network modelling would require the implementation of advanced load flow calculations that go beyond the scope of the tool developed and might hinder the possibility of running general although simplified analyses. In addition, for strategic assessments (and not detailed design) of MG, as is the purpose of WPH, the difference in the impact on radial or weakly-meshed networks can be reasonably neglected. It is therefore assumed here that each distribution network is operated radially from the GSP point to the end users. Furthermore, it is assumed that the model is composed of well-balanced three-phase circuits and transformers. A graphical representation of a generic distribution network with various loads and distributed generators connected is shown in Figure 4.1.

Each voltage level in the GDS tool is modelled trough different *modules*. A module is composed of a substation with the relevant transformers, the low voltage bus-bar of that substation, and a number of feeders connected to that bus-bar. Thus, when modelling a distribution network it is possible either to define as many modules as substations in the real network in order to obtain a totally precise but large model, or to define a smaller number of modules that would capture the key characteristics of the network. The latter approach is the most suitable for strategic analyses of large microgrid deployment in different countries. However, more accurate studies for targeted networks can be run in order to refine some specific details.

The design of a module is flexible, as it is possible to choose the characteristics of the transformers (capacity, impedance, no-load losses at rated power and load losses at rated power), the number of feeders connected to the bus-bar, their type (overhead line, cable or mixed), their length, as well as different tapering configurations and load connections.

As a result, two modules differ if any of the previous inputs are different. An example of modules for a LV network in the UK is shown in Figure 4.2.

Owing to the differences existing between each voltage level, particularly with regard to the connection of load, DG and lower voltage substations to the feeders, the main configuration of the modules is typically slightly dissimilar for each voltage level.

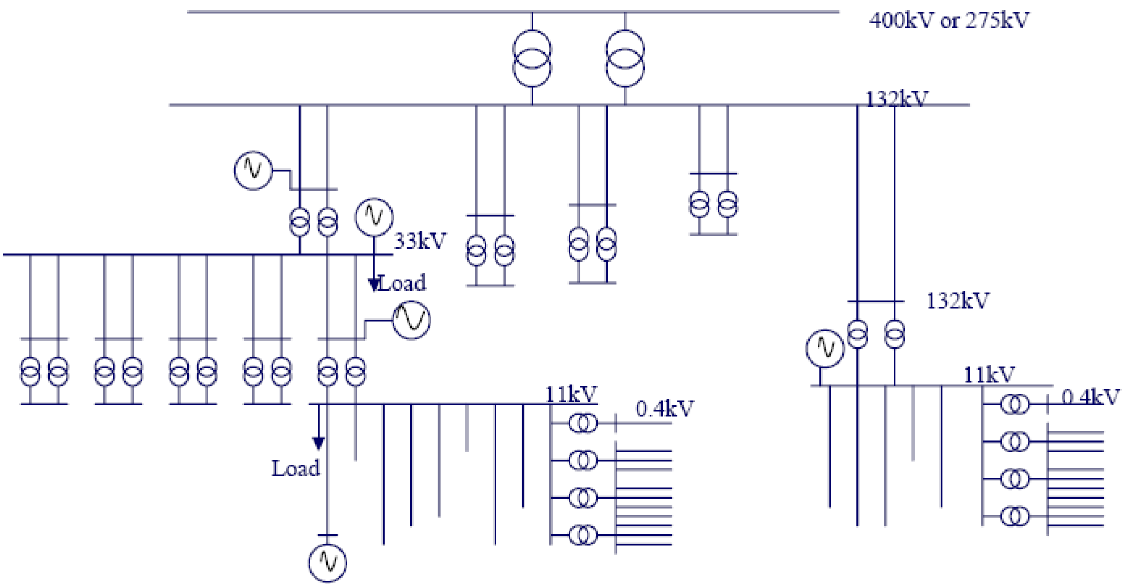
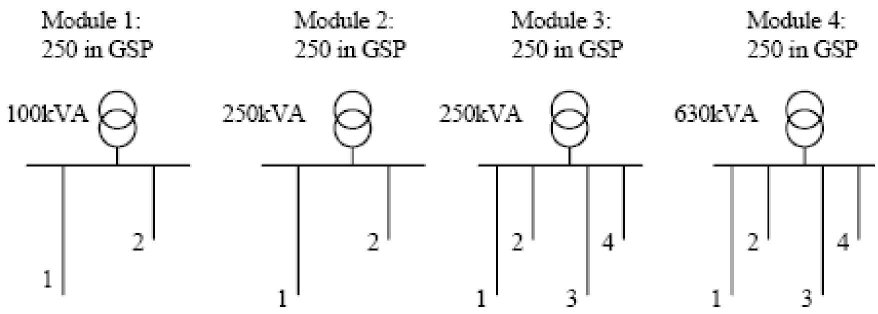


Figure 4.1. Example of GDS model network representation (UK).

0.4kV modules in GSP network



The urban network is composed of 250 of each 0.4kV module.

0.4kV module	Circuits	Type	Size		Length (km)	% of load	Load distribution
			Current network	Reference network			
Module 1	Circuit 1	UG	50 mm^2	70/50 mm^2	0.1	40	U.D.
	Circuit 2	UG	50 mm^2	95/50 mm^2	0.4	60	U.D.
Module 2	Circuit 1	UG	95 mm^2	185/95 mm^2	0.1	45	U.D.
	Circuit 2	UG	95 mm^2	300/95 mm^2	0.4	55	U.D.
Module 3	Circuit 1	UG	50 mm^2	50 mm^2	0.1	15	U.D.
	Circuit 2	UG	50 mm^2	95/50 mm^2	0.4	20	U.D.
	Circuit 3	UG	50 mm^2	185/50 mm^2	0.1	30	U.D.
	Circuit 4	UG	95 mm^2	185/95 mm^2	0.4	35	U.D.
Module 4	Circuit 1	UG	70 mm^2	185/70 mm^2	0.1	15	U.D.
	Circuit 2	UG	95 mm^2	300/95 mm^2	0.4	20	U.D.
	Circuit 3	UG	95 mm^2	300/95 mm^2	0.1	30	U.D.
	Circuit 4	UG	185/95 mm^2	185/95 mm^2	0.4	35	U.D.

	Capacity (kVA)	No-load losses at rated power (kW)		Load losses at rated power (kW)		Impedance (%)
		Current network	Reference network	Current network	Reference network	
Module 1	100	0.32	0.21	2.15	1.475	5
Module 2	250	0.65	0.425	4.2	2.750	5
Module 3	250	0.65	0.425	4.2	2.750	5
Module 4	630	1.3	0.860	8.4	5.4	5

Figure 4.2. An example of typical low voltage modules in the GDS representation.

4.2.2 Load and generation data

Data on load and generation (for all the different technologies involved in the assessment) are organized according to typical hourly load profiles in nine characteristic days representative of the overall year. Hence, hourly, daily (weekday, Saturdays and Sundays) and seasonal load and generation profile variations can be captured and used for load flow analyses that could cover the whole year time span. In addition, different load types can be considered, *e.g.*, residential, industrial and commercial ones, as well as generation types, according to the specific country case. The distribution of loads and generators at each voltage level and along feeders is also modelled. Examples of the data gathered relevant to load/generation profiles in sampled countries are reported in Annex 2.

4.2.3 Network constraints and active management solutions

Among the various concerns that may arise due to large deployment of DG systems in distribution networks, the main technical barriers [5] refer to voltage management and thermal rating issues in rural areas and system fault level issues in urban areas. On these bases, it is assumed that reinforcement costs are limited to the upgrade costs of circuits and substations in rural networks, and the replacement cost of switchboards in urban networks.

The GDS tool can therefore quantify the amount of generation that can be connected to the distribution network without triggering any reinforcement cost, as well as the impact of alternative control actions. In particular, in order to prevent voltage rise effects (mainly in rural areas) the general practice of DSOs is to limit the capacity of the connected DG based on the extreme conditions of minimum load and maximum generation. If a larger generation capacity requires a connection, the basic solution chosen under passive management (PM) is to upgrade the existing circuit in order to decrease its impedance. It is supposed in the model that increasing the cross-section of a feeder at a given voltage level will only influence its resistance while the reactance remains roughly constant. Similarly, if the circuit thermal load capacity is exceeded, the network (and in case the substation) is reinforced. Hence, it is possible to price the cost of DG connection to the network.

However, the penetration level of DG systems could be increased by adopting AM strategies, such as generation curtailment, or coordinated voltage control by adjusting (on-load or off-load) tap changers and reactive compensators in order to limit possible voltage rise effect. The GDS tool entails an AM optimization algorithm aimed at finding the optimum between annualised investment (network investment and reactive power investment) and generation curtailment taking into account losses. More specific detailed are provided in the analyses run in Deliverable DH2.

Connection of rotating machinery (both generators and motors) to distribution networks contribute to system fault levels. This additional “fault in-feed” can result in the system FL to increase beyond the rating of existing switchgears, in which case the switchgear is required to be replaced with equipment of a higher fault rating. In order to address this issue, the GDS model assumes that the symmetrical fault contribution is equivalent to *five times* the rating of the generator. In addition, suitable assumptions are carried out for the contribution on upper voltage levels. If a rise in system fault level requires the switchgear to be replaced with equipment of a higher fault rating, the entire switchboard of a substation is replaced in the model. This is particularly the case in urban areas, where short cables are installed. A cheaper alternative to replacement of the switchgear, which is the solution chosen in the passive management policy, is represented by splitting the substations bus-bars. Hence, the impedance between two voltage systems doubles, reducing the fault current coming from the upper voltage levels.

4.2.4 Relevant outputs of the GDS model

In terms of outputs, the GDS model can provide information relevant on different microgrid penetration scenarios, with different generation typologies and penetration density, and different AM strategies. Hence, for each selected country or generic or specific network analysed, it is possible to assess the impact of microgrid operation in terms of:

- *network losses*, and then relevant economic and environmental cost of losses;
- *flows at the different substations*, and then potential impact of microgrids on network reinforcement deferral;
- *voltage drop profiles*, whose analysis leads to the possibility of evaluating network reinforcement deferral, as well as alternative design strategies not requiring network reinforcements (in case triggered by MG);
- *fault level* changes, hinting the potential need of switchboard substitution, with relevant costs;
- *impact of active management* strategies to overcome potential drawbacks arising from microgrid operation, and then assessment of the trade-off between larger micro-grid penetration (and relevant benefits) and cost of AM;
- *overall energy produced by microgrids*, allowing the estimation of primary energy saving and emission reduction from avoided fossil source consumption, due to RES deployment or high-efficiency cogeneration.

4.3 Distribution system statistical model

4.3.1 Prototype network creation

The GDS model illustrated above will be mainly adopted within WPH for analyses of MG within generic networks as they are present (currently or in perspective) in the selected countries studied. On the other hand, an alternative and more general approach to microgrid appraisal consists of addressing the impact of microgrids on *generic networks*, with given load density and generation characteristics, which however do not correspond to any specific network. With the tool discussed here, in particular, several different networks with *statistically similar* characteristics can be created, so as to provide meaningful system-wise results for a number of possible scenarios.

Suitable LV networks must then be *generated* in order to mimic the typical characteristics that can be encountered in urban or rural settlements. More specifically, the main variable when “creating” a network is represented by the position of consumers, which affects the “amount” of equipment used (network length). A specific tool (an evolution of the one presented in [6]) was thus developed to generate generic networks where realistic consumer positions are established through *fractal theory*-based algorithms, which prove to simulate well the characteristics of human settlements dictated by economic laws.
Different number and types of users can be created, so as to simulate a range of possible scenarios (topology, consumer distributions, types, and load density, in particular) in actual towns/cities (an example is shown in Figure 4.3) and rural areas (an example is shown in Figure 4.4). Distribution substations (whose number is an input to the tool) are sited accordingly to load centre calculation. The original network created by the tool is weakly meshed, and on the basis of simplified power flows is divided into a number of radial networks (one per each substation), so as to resemble the typical operation of LV networks in most countries. Each of these radial networks thus corresponds to a LV microgrid coupled to the MV network through a substation. Load flow analyses are run on an hourly basis over one year time span, with typical seasonal profiles and user loads (as for the GDS model). The annual calculations allow determining the cost of system losses (cables losses, transformer iron losses and load losses).

4.3.2 Network sizing

The network components are optimally sized according to the minimum life-cycle cost (LCC) methodology, balancing the annualised capital investments and maintenance costs and the operation cost (losses), according to the model discussed in [7]. As an alternative design strategy, also a circuit design based on maximum current capacity can be implemented. In particular, by providing a prefixed allowance for circuit sizing with respect to the simulated peak load, this approach allows simulation of more or less loaded networks and thus assessment of the impact of DG on current networks, rather than of design strategies. In addition, an innovative environmentally oriented design strategy could be put forward, in order to address the impact of MG within more sustainable network replacement scenarios.

As a major feature of the tool for WPH applications, network design strategies *with* or *without* DG can be carried out, thus allowing the evaluation of the impact of DG on current networks/microgrids, as well as the design of future MG entailing DG. Distribution network replacement profile scenarios based on the statistical tool are discussed in Chapter 8.

It is checked whether the network so generated meet given requirements for maximum voltage drop allowed, and, if not, how many voltage violations occur. This allows to estimate how big the requirement for AM or DSM strategies can be.

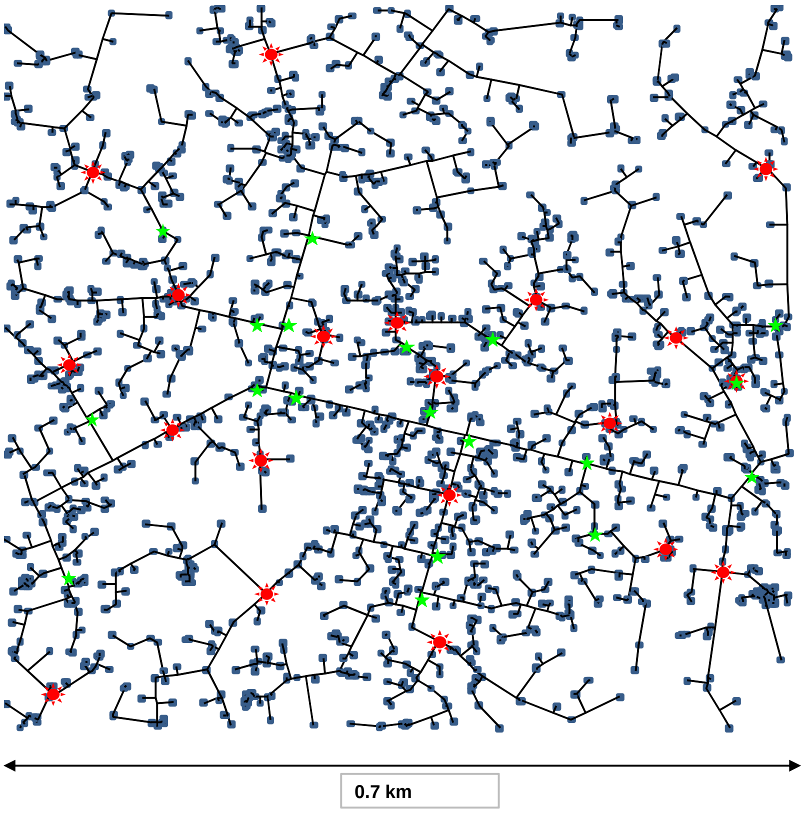


Figure 4.3. Example of *urban* network (2000 users) generated by the fractal tool, with location of 20 substations (in red) and open points (in green).

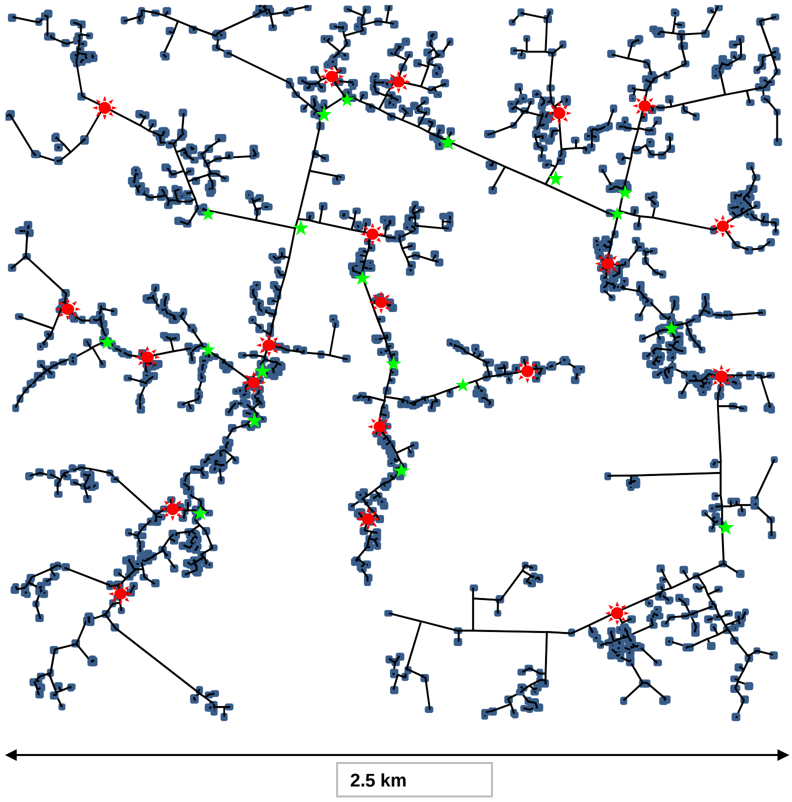


Figure 4.4. Example of *rural* network (2000 users) generated by the fractal tool, with location of 30 substations (in red) and open points (in green).

4.3.3 DG models

The fractal tool developed enables to assess the impact of different distribution network design strategies for different scenarios and solutions (number of substations, for instance), seeking the optimal configuration with respect to losses and with checks on voltage drops. In addition, it enables to assess the impact of different levels of penetration and typologies of DG technologies within LV MG. More specifically, it is possible to study the impact of DG on current networks (design according to an LCA assessment, or with respect to maximum current) in terms of voltage rise or drop, as well as of thermal operation of components such cables, transformers, and so on, so as to assess potential investment deferral from microgrid operation. On the other hand, the network can also be optimized already taking into account the presence of DG at the planning stage. In this case, optimal future microgrid design strategies can be obtained. Relevant applications to modelling aspects are shown in Chapter 8.

Since the correlation between generation and load is the key point to affect microgrid operation, specific focus was put on developing adequate generation models. In particular, as CHP system are usually operated in heat-tracking mode, specific models for building thermal loads have been developed for different user typologies, and different prime movers such as Stirling engines, MTs, and ICEs have been implemented to follow the thermal load while cogenerating electricity at the same time. In order to study the *controllability* of microgrids, also electricity-oriented control strategies (such as electrical load-following strategy) have been implemented, with heat production following accordingly. Potential energy saving and environmental benefit outcomes from the various strategies are then assessed on the basis of the models described in Chapter 5. The presence of DH networks can also be envisaged in the model. In addition, other DG systems have been implemented, such as PV or micro-wind, so as to cover a range of situations as it could occur in different countries.

4.3.4 Utilization of the statistical network tool

Having at disposal a generic model for network creation is a key tool for addressing general problems when detailed data are not available. In particular, the model can be used to generate *prototype* networks, on whose basis to estimate the impact of DG penetration on current networks, to be turned into MG, rather than planning the green-field design of future MG. In particular, it can be estimated how micro-generation can affect current network investment, both by postponing it or anticipating it because of reverse power flows, how to mitigate DG impact through AM/DSM strategies, and how DG impacts on losses and emissions in different generation scenarios. In addition, optimal microgrid design strategies, according to alternative criteria, can be addressed, so as to give an overall picture of the technical, energy, environmental, and economic potential of microgrids in long-term scenarios. The useful outputs from the model, to be used for post-processing analyses, are in practice the same as for the GDS model described above.
In Chapter 8, general replacement profile scenarios are modelled through the fractal tool, also as a support of the microgrid road-mapping scenarios developed in Chapter 9.

4.3.5 Illustrative example for LV network assessment

As an illustrative example of the fractal tool for network assessment of existing networks, let us consider a typical LV distribution network in the UK long about 6.3 km and serving 500 users through 6 11/0.4 kV substations. A typical distribution of users with load profiles as provided in Annex 2.5 is considered.
In the analysis illustrated here, the circuits and the substation transformers have been sized on the basis of the annual peak flows, with an allowance of 10%. In this way, a "loaded" network can be simulated, for which the impact of different extents of microgeneration penetration can be assessed. In particular, the mix of DG simulated is represented by 90% natural gas micro-CHP systems (1-kWe Stirling engines) and 10% 25-kWe MTs. In addition, starting from typical loads (electrical load patterns are provided in Annex 2.5), two different control strategies have been simulated, namely, thermal load-following and electrical load-following control strategy. The DG penetration level (defined as ratio of number of customers with DG to overall number of customers) has been varied from 0 to 100% by steps of 20%. Relevant output metrics for

the illustrative example are shown in Figure 4.5 with reference to the years of investment deferral for the most loaded substation (evaluated through the models discussed in Section 3.2) and in Figure 4.6 with reference to network losses.
From the results, it is possible to appreciate how with increasing level of DG penetration the investment deferral increase consistently when DG follows electricity (such control strategy is indeed more “grid-oriented”), while for heat following the investment deferral even decreases after a maximum at 60% of penetration, due to the presence of counter-flows caused by uncorrelated generation and demand. However, for reasonably expected levels of DG penetration up to 20% both control strategies perform in the same way. Similarly, for losses analysis it can be seen how network losses decrease substantially for increasing amount of DG, with no significant performance spread between the two strategies up to 20% penetration level.
Although only for illustrative purposes, the example shown here highlights potential use of the tool developed as well as typical analyses that can be run for assessment of the MG impact on current networks.

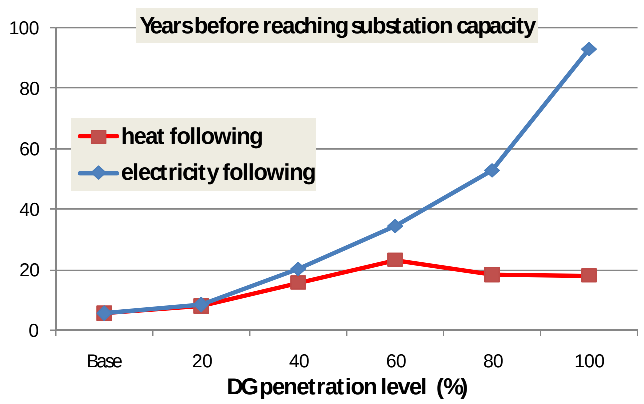


Figure 4.5. Assessment of the infrastructure deferral from DG in the case study illustrative example.

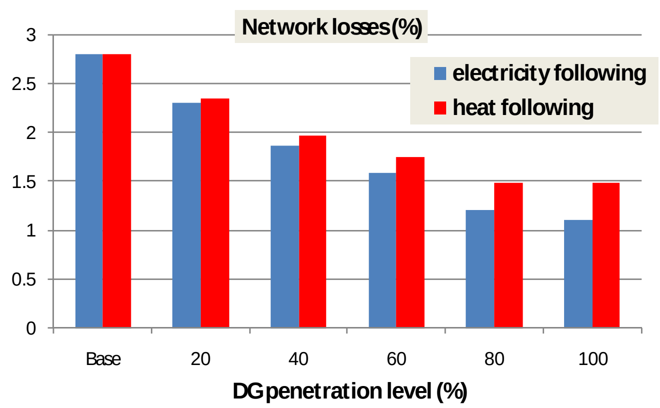


Figure 4.6. Assessment of network losses decrease from DG in the case study illustrative example.

4.4 Impact of large scale penetration of microgrids on the operation and development of central generation and transmission system

This section presents the general approach and models developed by Imperial in WPH to assess the impact of large deployment of microgrids on generation and transmission system operation and development. In addition, the role of microgrids in terms of increasing flexibility in future power systems is discussed and highlighted. The results from these models can also be exploited for the environmental analyses illustrated in Chapter 5, while the general consideration developed are used to formulate the microgrid evolution roadmap described in Chapter 9.

4.4.1 Microgrid potential impact on generation system operation and development

As widely discussed in Chapter 2, power generation by small-scale DG systems is characterised by intermittent, less predictable and controllable power output, which is caused either by the natural variability of environmental conditions (for RES) or by a certain operational mode (for instance, heat-tracking for CHP). In a microgrid, the control of the output of these DG systems together with responsive loads and smart appliances is enhanced so it can be used to support efficient system operation and development. These characteristics influence directly the operation of power systems at a transmission level (generation and transmission), besides having an impact on distribution networks, as discussed earlier in this chapter. Depending on the operating timeframe considered, microgrid operation may influence short-term balancing and long-term capacity provision in order to keep the system reliability and energy supply power quality levels within the permissible limits. The extent to which microgrids influence the power system depends foremost on their penetration level, besides the specific generation characteristics of each technology.

In terms of short-term balancing, apart from the conventional generation dynamic requirements that are discussed below in this chapter, micro-generation displaces operationally a certain amount of central generation. The characteristics of the displaced generation typically depend on the power system analysed and on the specific power plants being dispatched at the considered time. Indeed, since power plants are usually scheduled according to their marginal operating costs (merit order), in the absence of network constraints, micro generating units will displace marginal central generators, *i.e.*, the ones with high marginal costs. Dispatching of conventional generation usually occurs at a centralized level and regards units interfacing at a transmission level. On the other hand, power generation from microgrids contributes to supply demand that otherwise should be supplied by central generation. Hence, the equivalent residual demand as seen at the GSP from the transmission network, where market adjustments occur, is reduced. In other words, the microgrid impact at a transmission level can be modelled as equivalent demand decrease, or alternatively microgrids can also be represented to the higher system control hierarchy as equivalent aggregated generators and loads using the concept of Virtual Power Plant (VPP) (see also Section 9.1.2). This aspect is also dealt with in WPD.

Regardless of the modelling approach used, the microgrid operation knock-on effect is to make the units with higher operational costs go offline (with expectedly large fossil fuel and associated CO_2 emission savings), and other units to operate off-design. In particular, microgrids may affect the operational mode of these (now marginal) central generating units by increasing their start-up and shutdown number of cycles (particularly severely for steam turbine plants as opposed to gas plants) and reducing their equivalent full load hours or their capacity factor. It is critical that microgrids can provide system ancillary services that otherwise would be provided by the marginal central generating units. If not, the capacity of central generators cannot be displaced and they will operate more frequent in part loaded mode. Since power plants typically achieve highest efficiency when they are operated at full load, part load operation means lower efficiency, higher costs and higher emissions. Moreover, there are also requirements on minimum runtime, which for instance are particularly relevant for coal-fired or nuclear power plants, as well as perspective thermal plants equipped with Carbon Capture and Storage (CCS). A further issue refers to large CHP plants supplying DH networks, which, being typically heat-demand driven, are usually not displaced by MG.

On the above discussion, knowing marginal operating costs (and availability) of power plants, besides possible transmission capacity constraints, it is possible to simulate the merit order and determine the units that are substituted by microgrid operation. In this case, the correlation between microgrid generation and power system peak load (that can be increased by operating on the microgrid *controllability* potential) is the main driver to assess the impact of microgrids on the generation system.
Thereby, detailed simulations of the overall power system can be run (when possible) to address the impact of microgrids on the operation and the required capacity of central generation. As a general point, when not knowing the specific characteristics of the generation system, or relevant transmission network information for congestion appraisal, *reference* models can be adopted. Hence, the benefits that microgrids can bring to improve the capacity value of micro-generation (also exploiting controllable loads) and the relevant improvement in the energy and environmental performance (see Chapter 5) of the overall system operation can be quantified in an indicative way. Evolution of the bulk generation obviously brings about a number of implications also in terms of the environmental benefits brought by MG, in the light of increasing penetration of higher-efficiency and lower-carbon technologies such as for instance CCGT or CCS plants, besides RES. This issue is taken into account in the general micro-grid road-map formulation discussed in Section 9.2.

4.4.2 General aspects on transmission investment

Traditionally, network planners have determined the need for transmission network capacity across transmission boundaries based on security requirements and relevant probabilistic analyses [8]. Indeed historically the need for reliability has always been the most stringent parameter for design of transmission networks. The penetration of DG sources that may often be intermittent and less controllable (such as RES and CHP, which are often heat-driven) into distribution and transmission networks is changing the importance of the metrics through which transmission system performance is measured. In particular, it can be envisaged that for generation technologies with relatively low *capacity value*, such as intermittent renewable or uncontrollable heat-driven CHP, the traditional reliability based approaches for transmission planning are not adequate. In particular, high cost of transmission constraints occurring when capacity limits are reached could lead to install additional capacity in order to maintain efficiency of system operation.

In solving transmission planning problem, the model developed balances the cost of transmission constraints with the cost of increasing the transfer capability of transmission system. Transmission constraint costs occur when merit generators are constrained off and higher cost generators are constrained on due to transmission limitation. It is intuitive that, from a system perspective, the cost of constraining merit generators off can be balanced by costs in increasing transmission capacity. Seeking for *optimal* investment, transmission capacity increase can be justified only if the benefits (congestion relieves) are greater than the costs (capital investment).

4.4.3 Transmission investment in WPH perspective

Following the above concepts, economically-based transmission network reinforcement involves optimisation of the costs of investment in new transmission capacity against the costs of operation of the system (i.e., cost of constraints and losses), as illustrated in Figure 4.7. In particular, transmission investment is justified if the marginal network investment cost is less than the expected marginal constraint costs (over the lifetime of the new lines). Costs of investment and maintenance increase with network capacity, whereas costs of constraints and losses will decrease as capacity mitigates both these issues. The optimal network capacity is found at the minimum of the sum of these two costs. For investment higher than for the optimal network capacity, further capacity increment will result in higher total cost since the benefit, i.e., the reduction of transmission constraint cost, is less than the increase in transmission investment cost. The optimal transmission investment problem can thus be formulated in terms of a cost-benefit analysis (CBA) approach aimed at determining the amount of optimal transmission capacity to minimize the total cost of transmission constraints and losses versus capacity investment.

The aim of the studies carried out for transmission in WPH is to assess the impact of large scale microgrid deployment and operation on the transmission network especially on the development of transmission capacity (deferral of capacity reinforcement) and the impact of improving controllability of micro generators and controllable loads to the system operation costs.

In order to do so, a specific methodology and tool for analysis of transmission network investment with and without microgrids have been developed. The approach followed in the model is based upon CBA, as discussed earlier. Optimisation of network capacity according to the most economically efficient solution enables a better picture and quantification of the impact from non-conventional DG generators. More specifically, in the context of the studies in WPH on the impact of microgrid deployment on the transmission system, the CBA model developed for transmission system reinforcement was used to determine how much additional or deferred capacity would be driven through installation and operation of microgrids at certain points in the networks, while maintaining the economic optimality of the system development. In particular, the potential value of *controllability* of microgrids (for instance, by controlling CHP output or through suitable DSM strategies, including the option of installing *energy storage* systems) can be assessed. In the sequel, general issues on the model developed are presented.

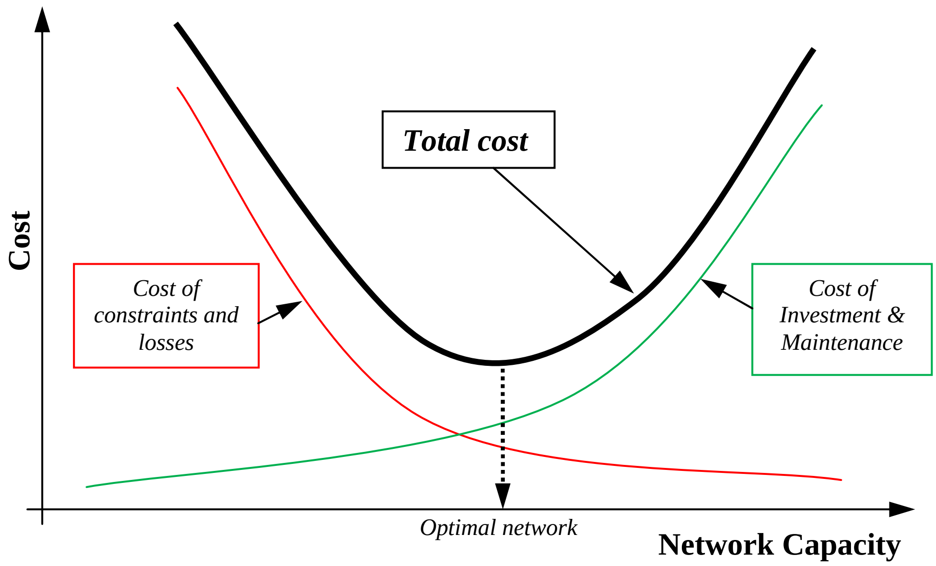


Figure 4.7. CBA approach to transmission investment optimisation.

4.4.4 *Methodology for assessment of optimal transmission investment considering the impact of microgrids*

A specific model has been developed to address the transmission expansion problem taking into account microgrid deployment in a market environment. The problem is formulated as a linear programming-based multi-period DC Optimal Power Flow problem. The objective is to minimise the present worth (PW) (this terminology is preferred here to *present value* in order to avoid misunderstandings with PV - photovoltaic) of the overall cost including the cost of additional transmission capacity investment, and the cost of re-dispatching generation to manage network congestion.

Hence, by simultaneously optimising these two terms, the optimal decisions for transmission investment can be determined and the optimal cost of transmission constraints can be quantified. At the same time, it is possible to assess the relevant impact of microgrids deployment and operation.

The objective function is set to total system costs, composed of cost of constraints and cost of network investment over the period under consideration, e.g., 30 years or more according to the life time of investment. Ideally, CBA should cover the life span of the transmission investment. PW–based values are thus used in order to compare cash flows of the costs at the different times on a meaningful basis. System operation simulation should be carried out by considering scenarios of daily and seasonal variations in generation and demand. In particular, future generation and demand scenarios should be specified considering changes during the life time of the transmission assets, possibly including commissioning of new and decommissioning of old generation plants. When detailed information is not available, suitable assumptions can be done in order to address the potential impact of microgrids in realistic future generation scenarios (see also the microgrid roadmap in Chapter 9). The effect of transmission losses on transmission investment is not directly modelled but the numerical value of losses and the relevant costs can be assessed *a posteriori* in scenarios with and without microgrids in order to estimate the microgrid impact on the system energy performance.

This general formulation enables us to take into account the impact of improving controllability of DGs and controllable loads in microgrids on transmission network from a double perspective, depending on how microgrids with RES and CHP impact at a GSP level, conventional connection border between transmission and distribution networks. More specifically, as already mentioned above, microgrid operation (with intrinsic local dispersed generation) could be such as to tail off the equivalent load as seen from the relevant GSP. In other words, the relevant distribution network including the microgrids under analysis is modelled as an equivalent load in the transmission model, with the relevant power flows being calculated on the basis of the simulations carried out at the distribution level. On the other hand, microgrid generation (above all if uncontrolled) could *in theory* even lead to a net power flow into the transmission network, so that the GSP equivalent would be modelled as negative demand. Likewise, aggregated microgrid energy outputs can be addressed within VPP generation models as injection in the transmission system. In any case, the CBA approach is able to evaluate the microgrid impact on the transmission network relative to the reference situation without microgrids, in terms of additional capacity required or capacity reinforcement deferral, as well as to foresee the impact of microgrids in future generation scenarios. Through such methodology, it is also possible to assess the value of *controllability* of microgrids with respect to uncontrolled microgrids.

As the methodology looks for the optimum in all the scenarios analysed (without microgrids, and with microgrids with different characteristics and penetration levels), comparison of the results lead to an unbiased evaluation of the actual impact of microgrids on the transmission infrastructure on a “like for like” basis. In addition, as the CBA for transmission investment takes into account the characteristics of the marginal plants operating in the market, the model developed implicitly also evaluates the impact of microgrid penetration on the conventional generation asset. In particular, it is possible to evaluate the existing generation assets that can be potentially displaced or the need for new generation assets that can be potentially postponed.

4.4.5 Generation and demand models

In order to reduce the computational time, typical load profiles for eight characteristic days are used in the model. The profiles capture temporal system load variation occurring in winter, summer, autumn and spring. Different profiles are also used for weekdays and weekends. In total, eight different load profiles can be used for the study, corresponding to the day length in Table 4.1. Further simplifications are carried out on the load profiling in order to reduce the data to few blocks of loads (while preserving the same amount of energy) and thus further speed up the calculations.

The load profiles can be either derived from general scenarios, or as a consequence of downstream calculations for distribution levels. In particular, specific scenarios can be addressed for microgrid penetration and operation in MV/LV distribution networks through the distribution network models illustrated previously, and then the relevant impact in terms of overall flows as seen from the GSP can be calculated. As mentioned above, in this outlook microgrid impact on the transmission system can be seen as an equivalent demand decrease due to decentralized generation. Also, the value of microgrid load control, particularly at peak times, can be assessed.

For each operating scenario (and with and without microgrids) the schedule of conventional and renewable generation (the model can include a number of different generating technologies) outputs is determined by using economic dispatch calculation. In the economic dispatch, since no transmission constraints are considered, the generation output of renewable generators (being the cheapest) is fully dispatched and thus taken as an input. The re-dispatching abides by the operational constraints that can be inputted to the model (maximum capacity, etc.). Hence, constraint costs (to be compared to network investment costs) can be evaluated by simulating a real market model on the basis of the one operating in the UK.

The approach relies on a range of assumptions, including (future) generation technology distributions, fuel costs, network reinforcement cost (that may also vary significantly), and so on. The accuracy of the results could depend significantly on the accuracy of the modelling process and on the reliability of the input data. However, regardless of the accuracy of the information provided, once reasonable assumptions are carried out the generality of the methodology allows for an unbiased comparative assessment of alternative microgrid scenarios, which is the main objective of this work. As a major point to be highlighted, whenever possible, the CBA should be conducted considering the entire transmission network (even a very simplified one) involved in the analysis (on a country-wise basis, for instance), as the application of CBA to boundaries would likely lead to overinvestment.

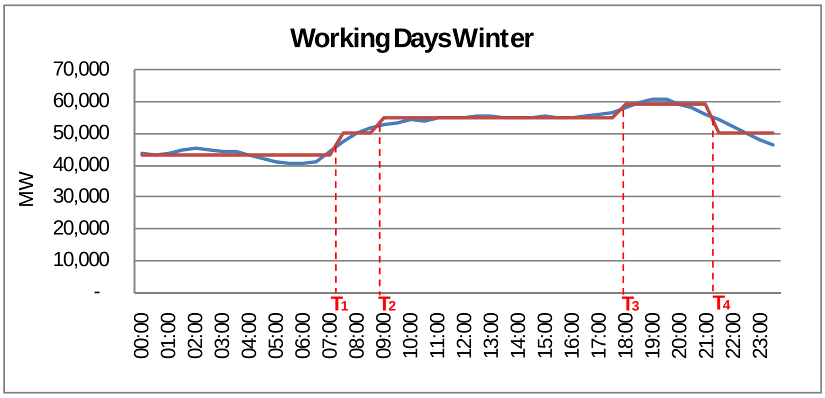


Figure 4.8. A daily load profile with aggregated intervals.

Table 4.1. The number of days per year for each characteristic day.

Day type	Number of days in a year
Summer working days	65
Summer weekends	26
Spring working days	65
Spring weekends	26
Autumn working days	65
Autumn weekends	26
Winter working days	66
Winter weekends	26

4.4.6 Application example: generic UK transmission system model

As an example of application of the model developed, a *generic* radial transmission system model which resembles the UK system (Figure 4.9) is used. Each bus-bar corresponds to a specific area in the UK. A tie line connecting two bus-bars represents a medium for power transfer between the two areas. Each node has a set of generators and a load attached.

Figure 4.2 reports an example of the capacity of generators and the magnitude of the load input to the model, as elaborated from data available from the UK Seven Year Statement for the 2009/2010 scenario [9]. The model also contains the information available for the planned transmission capacity for the 2009/2010 scenario and the approximate length of the transmission inter-connectors (Table Figure 4.3).

Microgrid impact assessment can be for instance carried out by modelling the microgids as passive VPPs or VPPs that can be controlled by the transmission system operator, on the basis of the analysis run through the distribution network models illustrated above. Relevant results are reported in Deliverable DH2.

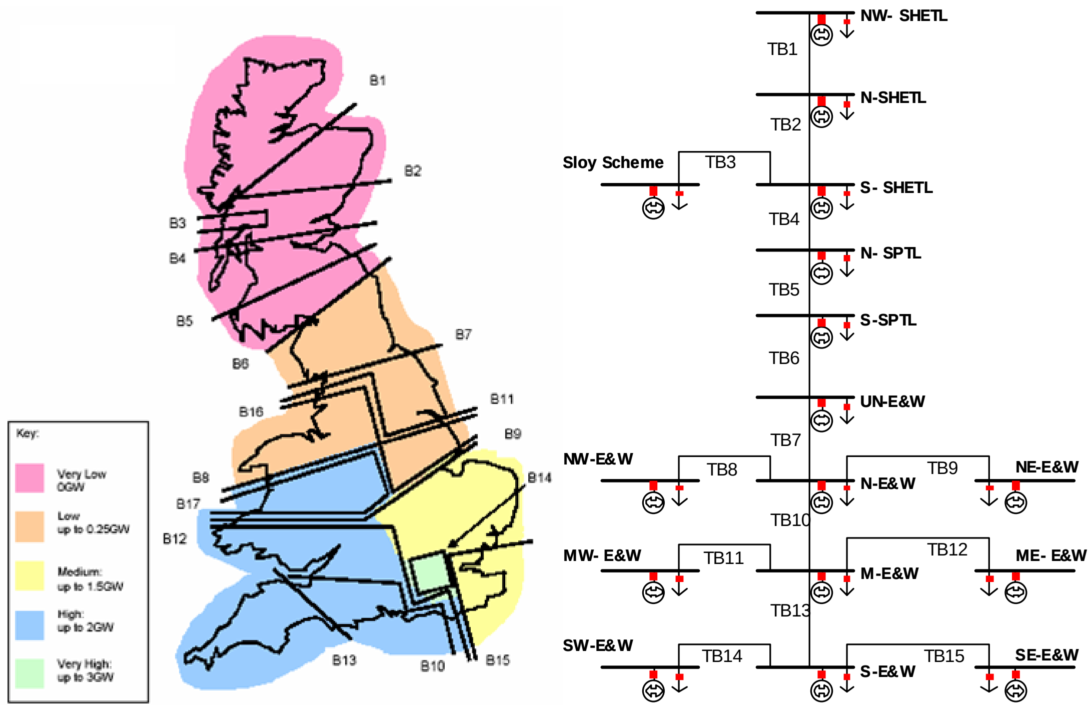


Figure 4.9. Generic UK transmission system model.

Table 4.2. Load and generation data.

Area	Bus bar	Peak Demand (MW)	Conventional generation capacity (MW)	Nuclear generation capacity (MW)
SCOTLAND	NW -SHETL	614	971	0
	N -SHETL	586	1554	0
	SLOY SCHEME	108	256	0
	S – SHETL	608	236	0
	N - SPTL	1239	2744	0
	S - SPTL	3318	4062	2490
	Total Scotland	6472	9823	2490
ENGLAND	UN-E&W	3561	4617	1207
	NW-E&W	8383	10135	3412
	NE-E&W	6638	13473	0
	N-E&W	**0**	**0**	0
	MW- E&W	8798	4235	0
	ME-E&W	820	6945	0
	M- E&W	**0**	**0**	0
	SW-E&W	13373	12922	1261
	SE-E&W	6639	13757	2246
	S- E&W	11005	2061	0
	Total England	59217	68145	8126
Total		65689	77968	10616

Table 4.3. Boundaries defined in the 16 bus system.

Boundary	From (Zone)	To (Zone)	Transmission capacity (MW)	Estimated length (km)
TB1	NW - SHETL	N- SHETL	400	100
TB2	N-SHETL	S-SHETL	1620	100
TB3	Sloy scheme	S-SHETL	220	50
TB4	S-SHETL	N-SPTL	1520	150
TB5	N-SPTL	S-SPTL	2550	50
TB6	S-SPTL	UN-E&W	2200	150
TB7	UN-E&W	N-E&W	3060	150
TB8	NW-E&W	N- E&W	1661	100
TB9	NE-E&W	N- E&W	5761	50
TB10	N- E&W	M-E&W	10603	100
TB11	MW-E&W	M-E&W	5974	100
TB12	ME-E&W	M-E&W	3957	50
TB13	M-E&W	S-E&W	11551	200
TB14	SW-E&W	S-E&W	5174	200
TB15	SE-E&W	S-E&W	6423	100

4.5 The role of flexibility provided by microgrids and dynamic impact on centralized generation

4.5.1 Centralized generation dynamic model and the increasing need for flexibility

The generation model described above within the transmission network assessment methodology can be referred to as "*static*" one, and provides first-approximation information on the average changes in the characteristics of conventional generation in power systems with MG. As discussed, in this approach MG can be seen as negative demand. The same applies for "large" RES such as typically wind farms, which can also be regarded as negative demand and is not specifically considered for system balancing purposes.

Deeper insights on the impact of microgrids on conventional generation can be obtained by adopting a "*dynamic*" approach. Such an approach takes into account the dynamic characteristics that power systems need to boast to reliably respond to rapid and large fluctuations in supply and demand. In conventional power systems, such flexibility is closely related to the ability of generation units to change their output when requested by the system operator. Different plant types are characterized by different flexibility levels (for instance related to the ability of ramping up and down, start up or shut down, and so on). Hence, typically a number of technologies are preferably used for base-load applications, whereas other can be used for peaking applications. For instance, it is well known that gas-fired plants, above all if operating in open cycle, are more flexible that coal-fired plants that are in turn more flexible than most current nuclear plants. The degree of flexibility can be related to either economical or technological reasons (as for CCS applications), or both.

Due to environmental reasons, future generation scenarios in Europe might be characterized by a mix of large generation plants relying on RES (and in particular wind), nuclear and CCS. As widely discussed above, RES output depends on the availability of natural sources, and can be highly variable, non-controllable and unpredictable. At the same time, current and old nuclear and CCS plants need to be operated in base-load mode. Thus, although with different characteristics, the centralized cleaner generation envisaged for the future will all affect the current practice of operating power system balancing. Indeed, whether because of the inflexibility of nuclear and CCS, or of the unpredictability and variability of natural resources, the system operator's objective of matching demand and supply will be more challenging relative to today's situation.

Looking at the current security practices, flexibility in response to a frequency deviation event (for instance due to generation failure or sudden demand change) is provided by a number of dispatchable (typically thermal or reservoir hydro) plants through:

- *frequency response* services, which entail all the response requirements from within 10 seconds from the frequency variation event (high-frequency response) to secondary response (up to 30 minutes), passing by the primary response service in the interval 10÷30 s from the event;
- *reserve* services, which entail the requirements to re-establish the initial frequency and demand-supply balancing situation prior to the frequency deviation event;
- *contingency reserve* services, which include all the actions that take place over longer time scales (above 5 hours), to adjust potential forecast errors and plant failures.

Reserve services are generally provided by plants rotating in synchronism with the bulk system (*spinning reserve*), to be deployed within 5÷10 minutes, as well as by non-synchronised alternatives (*standing reserve*), such as stand-by generators, to be deployed within some 20 minutes. Normally, spinning reserve is called in action first since it exhibits lower utilisation cost and is thus used to target relatively more frequent and smaller imbalances. On the other hand, standing reserve exhibits lower holding costs but has higher utilisation ones, so it is typically deployed for less frequent but more substantial imbalances.
The amount of reserve required is related to the probability of unbalances between generation and demand. Therefore, increasing penetration of RES, together with substantial presence of inflexible generation, is expected to call for increasing volume of reserve. In particular, spinning reserve is often inefficient and uneconomic, due to the

need for partial load operation. It is apparent then how the possibility of displacing spinning reserve through standing one could bring not only economic benefits (the main driver), but also environmental ones.

4.5.2 The role of flexibility that can be provided by microgrids

On the above premises, it is clear that in more or less close scenarios relevant to the major number of EU countries it will become crucial to have at disposal means capable to provide flexibility while displacing spinning reserve. From this standpoint, DSM and storage systems can be seen as efficient alternatives to conventional systems. In particular, a number of loads such as thermal-related ones (for heating and air conditioning) or equipment such as dish-washers and washing machines lend themselves well to implementation of control strategies enabling fast load reduction or increase. Similarly, as discussed earlier CHP systems that normally are operated under thermal load-following mode could be deployed for grid-related services, above all if equipped with heat storage systems capable to decouple the electrical and thermal loads. Therefore, MG with controllable loads and microgenerators are likely to represent a valuable source of flexibility in future more sustainable power systems. In particular, controllable thermal loads properly aggregated by the microgrid central controller (in case on the basis of distributed market logic) could provide demand reduction (or, in case, increase) services that could be called by the system operator when required. For system-wide applications, on the basis of what discussed above it is expected that the value of DSM in microgrids will be strongly related to the flexibility of the conventional generation mix, besides the penetration of RES such as wind and further inflexible generation such as CCS. This value is also expected to increase with the increase of the penetration of wind and inflexible sources. This aspect is indeed primarily considered in the roadmap scenario modeling developed in Chapter 9.

5. Microgrid energy and environmental assessment models

This Chapter discusses a number of models for energy and environmental assessment of power systems with microgrids. More specifically, an energy chain model is introduced to address the benefits from decentralized generation in terms of network losses and displaced centralized production. The energy chain model is then extended to entail environmental benefits through an emission factor approach. The issue of assessing global and local pollutants is then discussed, leading to the economy-equivalent framework of external cost analysis to internalize environmental costs. Finally, given the main role played by cogeneration in distributed applications, specific models for energy and environmental benefits brought by distributed cogeneration systems are presented and exemplified.

5.1 Environmental impact typologies assessed and models developed in WPH

By displacing conventional generation operation and decreasing overall network losses, MG based on RES and high-efficiency CHP systems can bring several environmental benefits. In particular, the potential environmental benefits to be analysed in WPH are:

- Higher efficiency for the overall energy sector;
- Primary energy saving, and thus decreased amount of non-renewable energy sources (also relevant to security of supply issues);
- Decreased pollutant emissions (with special focus on CO_2 emissions);
- Social benefits owing to lower environmental impact from energy generation, assessed for instance through external cost models [12][13] (see also the contribution of Imperial in WPG).

Energy efficiency itself, in terms of both better generation performance and lower distribution losses, brings a decreased amount of primary energy (PE) consumed when burning conventional non-renewable fossil fuels. In turn, this environmental benefit in terms of reduced *depletion of non-renewable natural resources* can be directly related to *security of supply* issues, as, in practice, lower amount of conventional fossil fuel needs to be used and, in case, imported. In addition, although not directly evaluated, the diversification of the primary energy sources (renewable or non-renewable) used as input for energy production is a further benefit from MG in terms of security of supply.

Suitable methodologies and models to fully address such benefits are detailed in the sequel. More specifically, the models presented here can be viewed as a data post-process of the information provided by the tools illustrated in the previous chapters.

5.2 Energy assessment models

5.2.1 Energy chain model for decentralized energy systems

Utilization of decentralized generation technologies avoids electricity flows from centralized power plants through transmission and (in part, depending on DG siting) distribution networks towards the final user. Transport losses associated to these flows are consequently avoided, which corresponds to emission reduction according to the bulk generation carbon footprint (see below). In addition, the possibility of producing *in loco* multiple energy vectors such as power and heat in cogeneration can bring further environmental benefits relative to conventional separate production (see Section 5.5). Hence, in order to catch the energy and emission benefits that microgrids could bring, robust methodologies are needed for unbiased comparison of alternative scenarios.

Considering *fuel-based energy systems*, the quantity of PE contained in the fuel (for instance based upon the fuel lower heating value, *LHV*) and needed to produce the different outputs represents a suitable evaluation metric. This leads to the so-called *energy chain* approach [14], which allows estimation of the overall energy system efficiency in the different transformations that occurs from one form of energy into another while undergoing industrial processes. Hence, through such an approach the generation of different energy output typologies can be related to a unique base reference, namely, primary energy, thus allowing an unbiased assessment of alternative energy systems.

In principle, the approach can also be extended to *energy systems with RES*. In this case, the environmental figures (primary energy and, as detailed below, pollutant emissions) relevant to the bulk energy system should take into account the (somehow, "for free") quota of energy produced by RES and are averaged out with the fuel-related figures. A further step could be undertaken through an LCA-based approach [15][16]. In this case, the environmental burden flows needed to build and decommission the renewable-based generator, namely, upstream (material extraction, transportation, construction, etc.) and downstream (plant decommissioning, waste disposal, etc.) of the energy generation stage, are included in the analyses. The impact of downstream and upstream environmental flows for fossil-based conventional generators are less relevant with respect to the energy generation stage, apart from some specific case such as, for instance, the share of methane lost during fuel extraction and transportation (see also DG1). Although running LCA (which requires detailed and specific data) is out of the scope of this work, it is important to highlight that in some inventories data can be provided on an LCA basis, which may justify possible inconsistencies when comparing different information sources.

Transmission and distribution losses can readily be taken into account within the energy chain model through the definition of transmission and distribution efficiency. In Figure 5.1 (source [14]) an example of the typical energy chain from fuels to final uses, namely, of fuel itself (for instance, gas for cooking purposes), electricity and heat, is shown. Figure 5.2 (source [14]) shows the same model applied to cogeneration, where a double energy vector is obtained (at higher conversion efficiency, as detailed below) from the same fuel input.

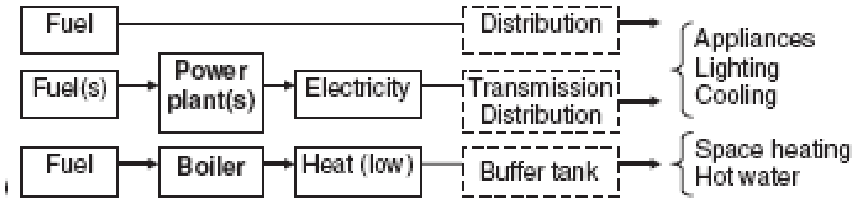


Figure 5.1. Fuel, heat and electricity energy chain model (Source [14]).

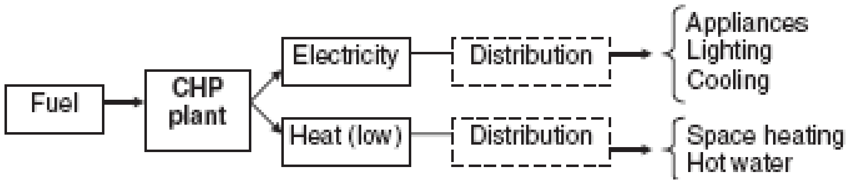


Figure 5.2. Heat-and-electricity cogeneration energy chain model (Source [14]).

5.2.2 *Primary energy rate (PER) for heat and electricity*

Given a generic energy output, the fuel consumption of any *combustion* equipment can be modelled through the relevant energy performance characteristics. In particular, with reference to the most used means for conventional energy production, electricity-only power plants are modelled through the electrical efficiency (generator electrical output W to fuel primary energy input F ratio), while heat-only boilers are modelled through the thermal efficiency (thermal output Q to fuel primary energy input F ratio). Likewise, CHP performance can be synthetically described through the cogeneration electrical efficiency η_e and the thermal efficiency η_t [17][18]:

$$\eta_e = \frac{W}{F}, \quad \eta_t = \frac{Q}{F}, \tag{5.1}$$

Within an energy chain approach, and in the presence of different energy outputs, generation means, and generation paradigms (such as centralized/decentralized ones), it is useful to characterize the performance of the various energy systems by defining the primary energy rate (*PER*) indicator as the (fuel) primary energy input needed to generate a certain amount of energy output. On the basis of this definition, for conventional electrical separate production (ESP) in power plants and thermal separate production (TSP) in boilers, the *PER* can be expressed as:

$$PER^{ESP} = \frac{1}{\eta^{ESP}} \qquad \text{(electricity)} \qquad (5.2)$$

$$PER^{TSP} = \frac{1}{\eta^{TSP}} \qquad \text{(heat)} \qquad (5.3)$$

In the above formulas, the terms η^{ESP} and η^{TSP} represent the electrical and thermal conventional generation efficiency in separate production, respectively.

A further definition could be derived with respect to the energy output *delivered to the user*. In this case, and with reference to the energy chain model, it is possible to redefine the above *PER* indicators as

$$PER^{ESP} = \frac{1}{\eta^{ESP} \cdot \eta_{TD}} \qquad \text{(electricity)} \qquad (5.4)$$

$$PER^{TSP} = \frac{1}{\eta^{TSP} \cdot \eta_{D}} \qquad \text{(heat)} \qquad (5.5)$$

where now η_{TD} and η_{D} account for the transmission and distribution electrical losses and distribution thermal losses (for instance, in a district heating (DH) network), respectively. Apparently, *PER*-based calculations reflect the philosophy of the energy chain model, as for the different energy outputs the relevant performance measure is represented by the fuel energy needed to get the considered output at a certain point of the energy chain (for instance, as delivered to the user).

The numerical values to assign to the reference *PER* can be arguable. Indeed, "static" values are suitable for first-hand evaluations and when further data are not available. On the other hand, for assessment of the impact of large microgrid penetration, a more *dynamic* analysis should be run. Indeed, high-efficiency microgrid operation would eventually affect the overall value of PER^{ESP} and PER^{TSP} by displacing lower efficiency power plants and boilers, thus increasing the equivalent value of η^{ESP} and η^{TSP} from the remaining conventional sources. However, evaluation of such benefits is not trivial, and, as also true for losses (see below), simulation analyses should be run for detailed assessments. When such analyses cannot be run, indicative estimates can be carried out through average values and by means of the *PER* indicators. Further discussions are also provided in Section 5.3.4.

5.2.3 Microgrids and primary energy losses

Electricity production from DG embedded at different network levels would face values of η_{TD} lower than for large power plants. An example of typical allocation of DG alternatives through the different network levels is reported in Figure 9.1. In this respect, MG at the LV level can provide the highest environmental benefits by avoiding both transmission and HV and LV distribution losses. The consequent avoided electrical losses can be significant, as in some countries transmission and distribution losses can reach around 10% of the produced energy (see Table 7.2 for current average losses in typical European networks).

In addition to electrical losses, also PE losses are intrinsic to electrical distribution efficiency. Indeed, the quantity of electrical energy dissipated by Joule effect corresponds to a certain amount of PE needed to produce it. In order to evaluate the primary energy losses, then, it is possible to introduce equivalent conventional generation means. For instance, let us consider the bulk power system generation in a country. It can be *averagely* modelled as an *equivalent power plant*, with a *PER* corresponding to the ratio of the total fuel energy input to the total energy produced. Similarly, an equivalent thermal system can be defined to model the heat generation in a certain areas, for instance a city[1]. However, the values of the reference *PER* should be calculated through scenario simulations, in the case of large penetration of MG able to change the large generator merit order, as discussed in Section 4.4, Section 4.5, and Chapter 9.

On the basis of the energy chain and *PER* models it is then possible to define the avoided *primary energy losses* ΔPE_L due to microgrid operation as

$$\Delta PE_L = \Delta P_L \cdot PER^{ESP} \tag{5.6}$$

where ΔP_L is the avoided *electrical* energy losses in the transportation networks due to power grid operation.
A similar formula could be applied also to thermal generation, in case, for instance in the presence of a large centralized DH system whose transportation losses are avoided though local cogeneration, for instance by means of DCHP.

It has to be pointed out that electrical losses are a quadratic function of the power flows, and so simulation analyses should preferably be run in order to capture the real benefits from microgrids in terms of avoided losses. In other words, transportation efficiency are actually a function of the load flows, so the value of MG displacing network flows at peak time is much higher than if displacing low-load flows.

5.3 Global environmental impact assessment models

5.3.1 Emission factor models

Concerning the emission characterization from fossil generation, any type of combustion equipment emits a certain amount of pollutants when burning a fuel. The characterization

[1] Due to the technical and economic constraints, heat can be efficiently transported over distances much shorter than for electricity, and as such relatively *local* generation references are more appropriate.

of the specific emissions of a given pollutant can be effectively evaluated on the basis of an *emission factor model* such as

$$m_p^X = \mu_p^X \cdot X \qquad (5.7)$$

where μ_p^X is the *emission factor* (*i.e.*, the *specific emissions* in [g/kWh]) for the generic pollutant *p*; m_p^X is the mass of pollutant *p* emitted while generating the useful energy product *X*. The emission factor μ_p^X depends upon several operating and structural variables, such as the specific equipment, partial load operation, age, state of maintenance, outdoor conditions, pollutant abatement systems, and so forth [18].

Often, emission factor values can be found in emission inventories as referred to the *fuel thermal input*. In this case, the *total* emissions of any given pollutant are assessed through the emission factor model with the relevant useful energy output *X* being represented by the fuel thermal content *F* [kWh_t] (for instance based on the fuel *LHV*) obtained when burning the fuel, which corresponds to the PE contained in the fuel:

$$m_p = \mu_p^F \cdot F \qquad (5.8)$$

It is worthwhile mentioning that this approach has the downside of being unable to provide any information on the emissions per unit of output and thus cannot take into proper account the conversion efficiency.
Hence, an alternative and more suitable approach is instead referred to the actual *output energy vector* from the generation device. In this case, the total emissions of any given pollutant are assessed through the emission factor model with the relevant useful energy output *X* being for instance electricity *W* for power plants or heat *Q* for boilers. When the generated vectors are manifold, such as in a CHP system, the pollutant mass m_p emitted can be expressed equivalently in terms of cogenerated electricity (as most often occurs) or cogenerated heat:

$$m_p = \mu_p^W \cdot W = \mu_p^Q \cdot Q \qquad (5.9)$$

Further emission factor models could be defined, for instance allocating the emissions to the *overall* energy output (electricity *plus* heat), or separately to the two energy vectors according to specific allocation techniques. However, the approaches illustrated here represent the most suitable ones to the purpose of the analyses performed here.

5.3.2 CO_2 emission characterization

Emission characterization of generic pollutants cannot in general be carried out, specifically depending on the combustion dynamics occurring in the specific device. Hence, emission figures are in general provided on the basis of average operational values or field trial measurements and should be generalized only carefully.

However, when referring to carbon dioxide emissions, an analytical approach can be carried out with very good approximation.

More specifically, if complete combustion is assumed (this is particularly reasonable if the device is operated with large excess air), CO_2 emissions can be worked out according to the characteristics of the chemical reaction, being a function of the carbon content in the fuel and of its *LHV* (*i.e.*, a function of the fuel itself) [18][19]. Thus, for a given fuel, the emission factor $\mu_{CO_2}^{F}$ referred to the primary energy F released when burning the fuel can be considered constant at first approximation. Then, since the relation between the fuel input and the generic energy output is given by the relevant efficiency, it is possible to draw an emission factor model for the conventional CO_2 emissions referred to the energy output as [20]

$$m_{CO_2} = \mu_{CO_2}^{F} \cdot F = \mu_{CO_2}^{X} \cdot X \qquad \Rightarrow \qquad \mu_{CO_2}^{X} = \frac{\mu_{CO_2}^{F}}{\eta_x} \tag{5.10}$$

where η_x is the relevant equivalent efficiency to generate the corresponding output X from the input F (for instance, the electrical efficiency η_e for generating electricity W in a power plant). Therefore, by means of this formulation it is straightforward to apply the energy chain model also to the environmental assessment by weighing the energy entries (and the correlated indices, such as energy saving) through the relevant CO_2 emission factor.

For more detailed analyses, also for CO_2 characterization, as for other pollutants, specific experimental measurements *in situ* for the given equipment should be carried out to evaluate the actual CO_2 emission factor for various operating conditions.

In order to have some order of magnitude, electricity from old coal-fired power plants typically results in emissions of about 0.75-1 tCO_2/MWh, whereas for natural gas technologies emissions would range from about 0.35 tCO_2/MWh (high-efficiency CCGT) and about 0.6 tCO_2/MWh (open-cycle gas turbines - GT) (see also Table 3.4).

5.3.3 Emission chain model for decentralized energy systems

In line with the discussions carried out in Section 5.2.1 and Section 5.2.3, it is possible to define an *emission chain model* in order to estimate the environmental benefits from DG (and, in particular, microgrids) in terms of emission reduction. More specifically, let us introduce reference emission factors for separate production $\mu_{CO_2}^{ESP}$ (electricity, from an equivalent power plant) and $\mu_{CO_2}^{TSP}$ (heat, from an equivalent boiler). Therefore, taking into account the energy chain model introduced above, it is apparent how microgrid operation, by potentially avoiding energy losses in the transportation networks, can also contribute to overall emission decrease ΔCO_2 corresponding to

$$\Delta CO_2 = \Delta P_L \cdot \mu_{CO_2}^{ESP} \tag{5.11}$$

where ΔP_L are the avoided energy losses due to power grid operation. A similar model could be applied in the presence of heat distribution.

As discussed above for the *PER*, large exploitation of high-efficiency MG displacing low-efficiency high-emission power plants would make the overall emission factor $\mu_{CO_2}^{ESP}$ decrease. If on the one hand this would diminish the environmental benefits due to losses reduction ($\mu_{CO_2}^{ESP}$ should be recalculated with the new decreased loads, if MG are simulated as equivalent loads), on the other hand the overall emission reduction due to decentralized higher efficiency operation relative to the current system should be acknowledged as well. This calculation can be carried out on the basis of the most suitable generation model (see Section 4.5).

With regard to fossil fuels and CHP operation, useful models capable to yield a clearer picture of the actual benefits from microgrids entailing cogeneration systems (as it is expected in most installations around Europe) are shown in Section 5.5.3.

5.3.4 Rationales and discussions for selecting the reference scenario for energy and environmental assessment

Due to the interaction of manifold factors, simulations of the bulk energy system with MG should be run in order to properly assess the energy and environmental benefits according to the models illustrated in this chapter and in the previous chapters. Furthermore, scenario analyses over several years should be in case run, as the average emission reduction could decrease with microgrid penetration, as at first the most expensive (and, likely, polluting) fossil power capacity would be displaced, and after that more efficient and less polluting ones. In this respect, the micro-grid roadmap illustrated in Section 9.2 provides useful indications. However, as detailed simulations are in practice tough to run, average values of the parameters involved in the analysis can be taken as reference in scenario analyses. More specifically, when detailed simulations cannot be run, indicative values must be assigned to the entries involved in the energy and environmental models introduced. Such values may depend on the purpose of the analysis. In particular, with respect to electricity generation, it is apparent that the numerical values to assign to the parameters η^{ESP} and $\mu_{CO_2}^{ESP}$ play a fundamental role. Synthesizing the issue, it is possible to consider two basic cases for addressing the evaluation of microgrids:

1. η^{ESP} (or PER^{ESP}) and $\mu_{CO_2}^{ESP}$ are estimated on the basis of *average* values relevant to the operation of the power system as a whole. In this case, average and practical indications can be provided in terms of the avoided energy and environmental burden.
2. η^{ESP} (or PER^{ESP}) and $\mu_{CO_2}^{ESP}$ are estimated on the basis of the "*marginal power plant*", according to the argument that DG sources are likely to displace the operation of the

more expensive, lower-efficiency and higher-emission power plants coming into operation.

Of course, both approaches are approximated, and an ideal analysis would consider the characteristics of the *actual* power plant typologies in operation [21], possibly by simulation of the overall power system [22].

Considering this aspect of the analysis represents a key point in the microgrid assessment. In this context, in fact, it is important to remind that losses are a quadratic function of loads and power flows. Hence, operation of MG in the more heavily network loading times can be significantly more environmentally effective than as estimated from an average value-based analysis. For instance, in the UK the CO_2 emission intensity from *marginal* plants is estimated to be equal to 570 g/kWh$_e$ [23], so that losses reduction corresponding to peak network operation improves consistently with respect to considering the estimated average value of 430 g/kWh$_e$. Of course, the capacity of MG to displace peaking emissions is also relevant to the specific network, and should in case drive the selection of the installed DG. For instance, in the UK the majority of losses are generated in winter evening periods, representing the annual peak times in most of networks spread over the territory. This is a period of expected micro-CHP operation, so that the microgrid operation could significantly reduce the loading when networks are most stressed, and the relevant high losses. In other countries, above all in Southern Europe, peak electricity is generated at the central hours of summertime days, when air conditioners are fully operated. In these cases, PV generation correlated with the peak load would represent a sounder option.

On the above considerations, not accounting for the "dynamics" of power system operation (see also Section 4.5) might lead to biased environmental assessments [22], as well as send biased economic signals to the market [21]. On the other hand, it must be highlighted that the presence of competitive energy markets might render an environmental assessment based on marginal plant references extremely uncertain. Indeed, typically nuclear, CCS and some hydro-sources are operated with flat profiles, to cover the base load demand, so that the load-following operation is left to other, more polluting, plant typologies (Section 4.5). Nevertheless, establishing indicative figures for marginal emission intensities might be a daunting task, since fast-changing energy market scenarios would boost the utilization of different sources, case by case. For instance, while low-efficiency and high-emission coal plants are claimed to be soon phased out in most countries, their utilization has lately come back *in auge* due to high gas prices that might make them more convenient with respect to modern high-efficiency CCGTs.

For the purposes of this work, analyses with average and/or marginal values are considered in WPH when more detailed data are not available and thus it is not possible to run the generation models described in Section 4.5.

A further refinement of the analysis could also account for the performance variation trend for both DG and SP reference systems, which would call for relevant information upon the trend forecast. In particular, for energy and environmental benefits, also a comparison with new (centralized) plants that would be used if the DG systems were not installed could be carried out [24]. This approach is sound for general comparison purposes and is relevant to microgrid scenario analyses.

5.4 Local environmental impact indicators and energy externalities

5.4.1 Emission balances as approximated environmental impact assessment tool

The energy and environmental assessment models introduced in the above sections implicitly rely on *metrics* that are based on balances between alternative generation options (in particular, envisaging the presence or not of microgrids).
In this respect, the simplest approach to environmental impact assessment of energy systems can be carried out on the basis of emissions only. Hence, when comparing two energy scenarios, and in particular scenarios with the presence of MG characterized by different generation mixes and conventional scenarios, it is possible to define an *emission balance* such as

$$\Delta m_p = m_p - m_p^{\mu G} \qquad (5.12)$$

where $m_p^{\mu G}$ is the mass of the specific pollutant *p* emitted in the presence of MG, whereas m_p refers to the conventional situation without microgrids. Positive values of the above emission balance would mean net emission reduction owing to microgrid deployment. Besides, since in different scenarios the amount of energy generated may be different, it may convenient to rescale conventionally the emission balance with respect to the overall produced electricity, so as to have

$$\Delta \mu_p = \mu_p - \mu_p^{\mu G} \qquad (5.13)$$

where μ is now the *emission factor* with respect to the electricity generated (g/kWh$_e$) in the relevant scenario.

The above emission balances provide a good approximation for estimating the environmental impact due to alternative energy scenarios. However, for comprehensive analyses more detailed models (discussed below) are needed. In particular, it should be recognized that emission quantities alone (and then emission balances) can give only indicative results when applied to *local* air pollutants such as NOx, SOx, CO, etc, whose impact radius is relatively limited (within thousands of kilometres) and depend on the pollutant dispersion characteristics in the atmosphere. On the other hand, as the GHG effects of CO_2, CH_4, etc. are *global* (world-wise), comparison of emission scenarios through emission balances are also indicative of the overall comparative effects [25]. Hence, the environmental assessment models introduced above have been dubbed as *global*, while the further discussion in the present section refer more to *local* models. As for GHG assessment, also for PE saving assessment it is possible to consider global models, in which case the relevant concept of "global" can be referred case by case to a specific country, the EU, the whole geographical Europe, and so on.

In general, more advanced tools are needed if willing to address simultaneously local and global environmental effects.

5.4.2 Refined environmental impact models for local pollutants

Refined models to address environmental impact assessment of MG with reference to local pollutants would require adoption of fluid-dynamics models of the pollutant dispersion in the atmosphere [26], accounting for the morphologic and meteorological characteristics of the site where microgrids systems and (for comparison purposes) conventional large power plants are sited. In fact, when addressing *local* effect from pollutant emissions the air pollution effects depend consistently on the relevant dispersion characteristics (height of stack, exhaust speed, wind intensity, natural or constructed obstacles, etc.) [26].

On the basis of the local air dispersion characteristics, pollutant emissions from a generation source bring about a certain spatial and temporal distribution of pollutant concentration. Among the possible approaches, an estimate of the environmental-sanitary risk (which is a direct measure of environmental impact) can be carried out through the *pathways* of transfer from air pollutant emission quantity to the *dose* assimilated by the man (or other relevant *receptors* such as ecosystems, monuments, and so forth) through various stages, including contact with soil, water, crops, and so on. The final results of this cumbersome assessment process are the most adequate to identify the real damage that a certain emission source brings about on the exposed subjects. A schematic representation of the various stages of the sanitary risk assessment process described in shown in Figure 5.3 (modified from [25]).

Although the above procedure is in principle the most correct to apply for environmental impact assessment, running this kind of analyses is often challenging, also due to lack of adequate data. In addition, for generic and indicative assessments of alternative energy scenarios, it is neither practical nor often possible going into details, also considering the high uncertainty affecting the results. Hence, indicative analyses typically resort to average numerical values from previous studies addressing these issues. Therefore, the next step lies in the identification of suitable numerical inputs to the analysis.

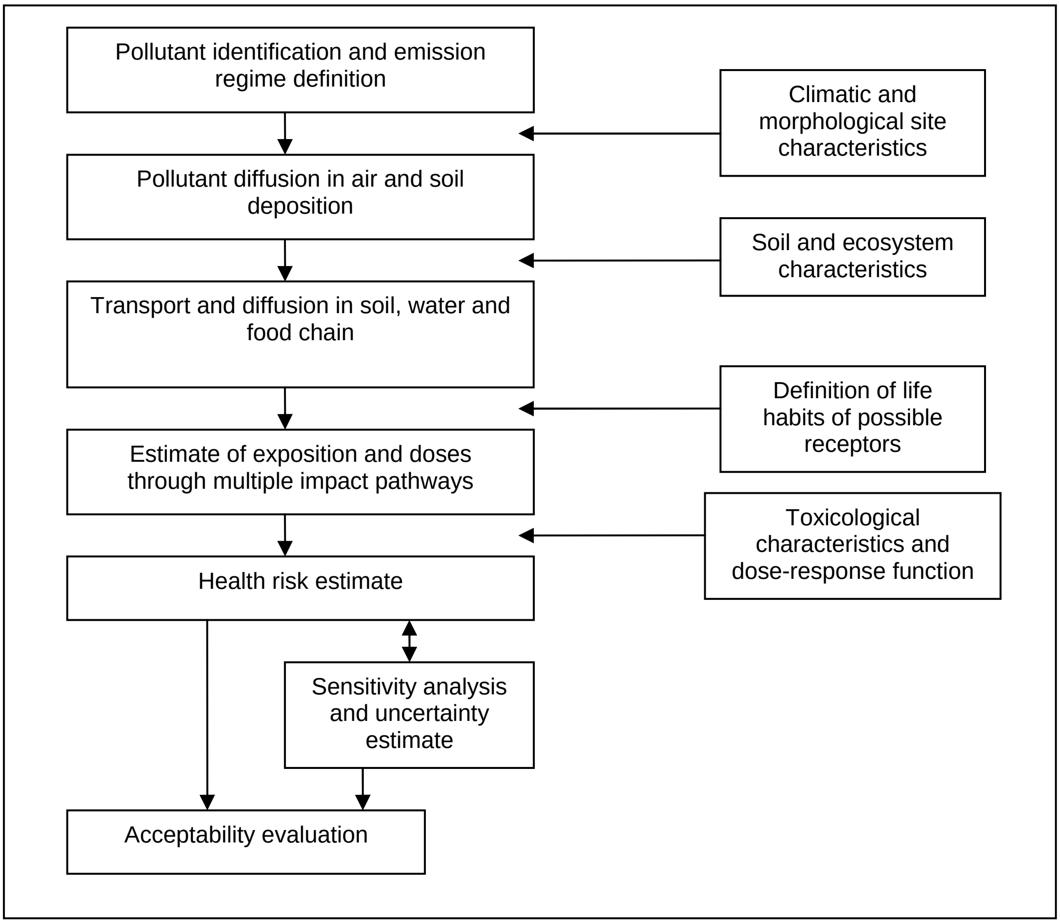


Figure 5.3. Schematic flow-chart for sanitary risk estimate.

5.4.3 *Environmental costs of energy and energy externalities*

Among the proposed approaches, a systematic framework to perform environmental impact analyses, based on identifying the *external cost* or *externalities* (see also WPG for further contribution from Imperial in this respect) from electricity generation, has been developed at a European level within the ExternE project [13]. In this framework, a *bottom-up* approach is introduced, based on the concept of tracking back event occurrences to their original causes through the determination of relevant *impact pathways*, as illustrated above. This methodology first includes the description of the considered technology and the identification of the source emissions (as performed through the microgrid models and scenarios developed), then the analysis of dispersion of the emissions on the territory (through advanced fluid-dynamics codes), the identification of the *receptors* with determination of relevant *dose-response functions* for assessing the potential damages, and finally the *economic* quantification of the damages. This economic quantification, run through suitable economic methodologies, refers to estimating the costs on the society due to pollutant emissions, which are not addressed by the emission source. As such, these costs are *external* to market economic assessments, so that in practice *external costs* can be seen as *social environmental costs* borne by the entire society.

Procedures such the one considered in the ExternE project lead to average cost values per units of pollutant emitted, on which basis further numerical analyses can be run starting from the relevant emission quantities in the considered scenarios. Although the numerical values depend on the specific assumptions used in the project and change country by country, at first approximation average figures can be used for scenario comparisons, as exemplified in the analyses run within WPG. Indeed, given its simplicity, the approach based on emission scenario formulation and calculation of the relevant externality based on the emitted fluxes and through given externality parameters is typically applied for general assessments, and as such will also be applied in this work. In particular, application of a relatively simplified methodology is justified in the presence of high-level scenario comparisons, where there is no information about the plant siting and the other needed relevant characteristics, as in the studies considered here.

On these above bases, the external cost C_p associated with a given emission flow of the pollutant p can be expressed as

$$C_p = \pi_p \cdot \mu_p \cdot W \tag{5.14}$$

where μ_p is the emission factor, π_p is the external cost for the specific pollutant, and W is the relevant amount of electricity considered in the analysis.

Further models for environmental impact assessment of microgrid penetration scenarios with respect to the *status quo*, among which the ones based on external costs, are briefly discussed below.

5.4.4 Possible general classifications of environmental impact indicators

Externality calculation based on impact pathways or emission flux scenarios can be framed within more general schematizations. In particular, it is possible to identify two general impact categories [25]:

- "*Source-side*" indicators: these indicators synthetically identify the *environmental pressure* due to the presence of hazardous emission sources. From this point of view, the most synthetic indicators are the *emission factors*, that link in a straightforward way the amount of useful product (energy) to the environmental cost of it (pollutant emissions).
- "*Receptor-side*" indicators: these indicators synthetically identify the *effects* that the emission source cause on the various receptor typologies, namely, population, ecosystems, monuments, and so forth. For instance, per-volume pollutant concentration levels represent an example of such indicators.

Another possible classification of indicators is based on the cause-effect level of interaction, that is, on the level of interaction between sources and receptors. Among the possible typologies of environmental indicators it is possible to mention, for instance [25]:

- *Environmental pressure indicators:* these indicators quantify the level of environmental pressure due to the presence of the emission source in a given area. Such indicators can be *integral* (for instance NO_x mass emitted in a given time frame), or *specific (*NO_x mass emitted per kWh generated). In addition, such indicators can be grouped in *simple* (percentage CO_2 emission reduction, for instance) or *compound* (sum of emission factors or of mass of pollutant emitted). The emission balances or the cogeneration indicators *PES and CO2ER* discussed below are examples of environmental pressure indicators.
- *Aggregated indicators*: these indicators are typically *compound* by means of weights that somehow quantify the effect over the final receptors, even without resorting to actual evaluation of such effects. For instance, it is possible to refer to this category when external costs are evaluated according to the cost of abatement systems [27]. Another typical example refers to aggregated indices such as the Global Warming Potential (*GWP*), expressed in terms of equivalent-CO_2 taken into account the relative effects of additional GHG pollutants such as CH_4 and N_2O with respect to CO_2 effects (see also WPG).
- *Integrated indicators*: to this category belong all those *compound* indicators whose weights that point out the potential effects over receptors are evaluated by means of the successive stages that lead to damage assessment. *External costs* evaluated according to the impact pathway methodology adopted in ExternE [13] are a typical example.

Of course, the different categories introduced are not mutually exclusive, and, on the contrary, the interaction typology among the first class of categories leads to generate the second class.

5.4.5 Other non-pollutant externalities

Without any presumption to be exhaustive, among other non-pollutant externalities that are associated to energy generation and that may be related to MG deployment it is possible to mention [27]:

- *Noise impact*: the "cost" of such externality is often already internalized in thermal generation plants (both large- and small-scale) through phono-absorbent materials in the plant building. On the other hand, it could be more relevant for other generation typologies, such as wind farms.
- *Visual impact:* large thermal power plants are often far from urban agglomerated and are not typically cause of large visual impact, which might instead be more relevant for large wind farms. On the other hand, small-scale systems to be applied in microgrids might represent some source of visual impact. However, in general PV systems do not produce a relevant impact, and might actually even be source of a *negative impact* (by adding glamour to the constructions). Similarly, small- or micro-

scale thermal systems, such as for cogeneration, in general exhibit stacks that are comparable (if not the same at all) with the ones for traditional boilers, so that no additional impact arises.

- *Land impact* due to land occupation. This impact is relevant to large thermal and hydro power plants or with relatively large spatial impact, such as wind turbines, whereas it is almost negligible for MG applications.

In the most general meaning of externality, it is possible to consider other elements that are not related, strictly speaking, to environmental damage, such as:

- External costs related to *security of supply* [27]) for a whole country, for instance of natural gas.
- *Depletion of non-renewable sources* such as fossil fuels, with the consequent potential missed opportunity for future generations to exploit such resources.

Relevant energy externalities will be considered in the successive analyses by exploiting the network models developed in this WP, with specific reference to primary energy saving (relevant to security of supply and depletion of non-renewable sources) and GHG emission reduction, in order to address some of the environmental benefits from microgrids.

5.5 Cogeneration assessment models

5.5.1 General issues on cogeneration assessment

Due to the foremost role that is envisaged in MG (in both Southern and Northern scenarios) for CHP systems, it is crucial to have a thorough picture of the benefits brought by cogeneration adoption. In particular, it is well known that combined production of heat and power in cogeneration is characterized by higher energy efficiency than electricity-only systems [17][18]. Hence, adoption of MG with decentralized cogeneration could increase the overall energy performance of the power system.
However, adequate models are needed in order to assess the actually benefits brought by cogeneration with respect to the conventional generation. In this respect, several performance indicators have been presented in the literature to evaluate the CHP plants characteristics [17][18].

The major issue with cogeneration performance assessment is related to the fact that the thermodynamic quality of the two products is quite different. This can be readily proven by simply thinking of the limitations to power generation from a thermal cycle as provided by Carnot's theorem. In this respect, a set of theories and indicators based on a second law-based approach have been put forward in order to assess cogeneration performance. However, several of these theories are still under developing, and their application to general cases may not be easy. Hence, in the sequel the focus will be set on energy (first law-based) indicators that can be easily and practically applied. In addition, some of these models or modified versions are adopted by regulation in several countries and at the European level [11] as the basis for providing incentives to proven high-efficiency systems.

5.5.2 Primary Energy Saving (PES) or Fuel Energy Saving Ratio (FESR)

Among the various performance indicators proposed, the Primary Energy Saving (*PES*) indicator lends itself particularly well to address the benefits brought by combined energy production in terms of fuel saving obtained with respect to the separate production of heat (in conventional boilers) and electricity (in power plants). The *PES* (also known as *FESR – Fuel Energy Savings Ratio*) is defined as [17]

$$PES = \frac{F^{SP} - F}{F^{SP}} = 1 - \frac{F}{PER^{ESP} \cdot W + PER^{TSP} \cdot Q} = 1 - \frac{F}{\dfrac{W}{\eta^{ESP} \cdot \eta_{TD}} + \dfrac{Q}{\eta^{TSP} \cdot \eta_{D}}} \quad (5.15)$$

In the above formula, *F* represents the fuel thermal input to the CHP plant in order to get the final energy output *W* and *Q*, while F^{SP} is the fuel thermal input to the equivalent models used as the SP references. The entry F^{SP} is evaluated by means of the *PER* for separate production of electricity (with conventional reference electrical efficiency η^{ESP}) and heat (with conventional reference thermal efficiency η^{TSP}).

In order to take into account the decentralized nature of cogeneration (in microgrids, in particular), such *PER* values also include electrical transmission and distribution losses (avoided by means of the local cogeneration), as well as heat distribution losses, if any (this could be the case of DH systems supplied by centralized boiler plants). In the *PES* formula above it is assumed that no electrical or thermal distribution losses occur with respect to cogenerated energy, that is, that they are negligible owing to users' proximity to generation, and thus *W* and *Q* also represent the energy delivered to the users. If heat networks or relatively large MG supplied by CHP systems were to be evaluated, *W* and *Q* should be divided by the relevant distribution efficiency in order to get the actual amount of energy to be cogenerated and fuel input to supply the demand. If network models are available, relevant balances should thus include network losses.

Considering the definitions of thermal and electrical efficiency, the *PES* can be rewritten as

$$PES = 1 - \frac{1}{\dfrac{\eta_e}{\eta^{ESP} \cdot \eta_{TD}} + \dfrac{\eta_t}{\eta^{TSP} \cdot \eta_{D}}} \quad (5.16)$$

which only depends on the CHP plant performance characteristics, besides the performance of the reference system (including network losses).

For general and indicative energy assessment of MG with cogeneration, the reference efficiencies could be evaluated in terms of average values for the overall power system and extensive thermal production on a certain area. In the latter case, average generation efficiency for current natural gas boilers can be estimated at around 0.7-0.8 for household level, while larger condensing boilers can operate with nominal efficiency up to 0.9-0.95

(also depending on the seasonal effects). However, for accurate analyses in line with the reasoning in Section 5.3.4, more detailed simulations should be carried out in order to address the system value of large cogeneration deployment (including transport losses assessment).

5.5.3 Cogeneration assessment: CO_2 emission reduction

The *PES* is a powerful and synthetic indicator to assess the energy saving potential of different CHP alternatives, and as such is also used for regulatory purposes in different countries and at a European level.
Following the same lines and taking into account the models discussed earlier in this chapter, it is possible introduce an analogous indicator capable to assess the potential reduction of CO_2 emissions and thus the reduced GHG environmental impact from CHP systems relative to SP. The *CO2ER* (*CO_2 Emission Reduction*) indicator [25] (as a special case of more general indicators for poly-generation systems [19][28]) can be generally defined as

$$CO2ER = \frac{m_{CO_2}^{SP} - m_{CO_2}}{m_{CO_2}^{SP}} \tag{5.17}$$

where m_{CO_2} is the CO_2 mass emitted by combustion of the fuel thermal input in order to cogenerate heat and electricity, while $m_{CO_2}^{SP}$ is the CO_2 mass emitted by combustion of the fuel thermal input F^{SP} in order to produce the same relevant amounts of energy in separate production according to reference generation technologies.
As for the *PES* indicator, *positive CO2ER* values mean that the production of a given amount of energy in cogeneration is more “effective” than the separate production of the same amount of energy, while *negative* values represent cases in which the combined production is less effective than the reference separate production of the same amount of energy.

Referring the CO_2 emissions in cogeneration to the fuel thermal input *F* and the ones from separate production to the relevant energy outputs *W* and *Q*, the *CO2ER* indicator can be further expressed as

$$CO2ER = 1 - \frac{\mu_{CO_2}^{F} \cdot F}{\mu_{CO_2}^{ESP} \cdot W + \mu_{CO_2}^{TSP} \cdot Q} \tag{5.18}$$

where $\mu_{CO_2}^{ESP}$ and $\mu_{CO_2}^{TSP}$ are the reference SP output-related emission factors, while $\mu_{CO_2}^{F}$ is the fuel-related emission factor input to the CHP system (gas, diesel, and so on).

The emission factors for the separate production can be evaluated according to what discussed in Section 5.3.4. Further discussions on the rationale for selecting the most suitable reference scenarios in cogeneration evaluation, as well as on the conceptual differences and similarities between *PES* and *CO2ER* indicators can be found in [19][29].

5.5.4 Cogeneration assessment: illustrative example

In order to provide a simple example of application of the methodology used for network evaluation of MG, let us consider the same case already illustrated in Section 4.3.5. The cogeneration indicators *FESR* and *CO2ER* have been implemented to post-process the network results from the fractal model developed. In the specific case study considered, the results for the two different control strategies already discussed and for the different penetration levels are shown in Figure 5.4. Average conventional generation electrical efficiency for the UK has been assumed equal to 40%, while the average emission factor has been assumed equal to 520 gCO_2/kWhe. For heating boilers, natural gas boilers with average efficiency of 0.8 have been assumed.

From the results, it can be appreciated how the electrical following strategy performs much worse than the thermal following one when evaluated on the basis of environmental metrics, contrarily to the network-related metrics analysed in Section 4.3.5. In fact, cogeneration benefits are maximized when the highest possible amount of thermal load is supplied through combined production, as occurs for thermal load following. Instead, in the electricity following case only a minor share of heat demand (the one correlated to electricity demand) is supplied by the relevant CHP system, while the remaining quota is covered by auxiliary boilers. For the same reason the environmental benefits increase substantially with increasing DG penetration, that is, with the share of customers that are served by CHP and not by conventional boilers.

Again, although only for illustrative purposes, the example shown here highlights practical applications of the tools and methodology developed, as well as the possible arising of conflicting objectives such as network benefits and environmental benefits relevant to demand supply when formulating suitable MG control strategies.

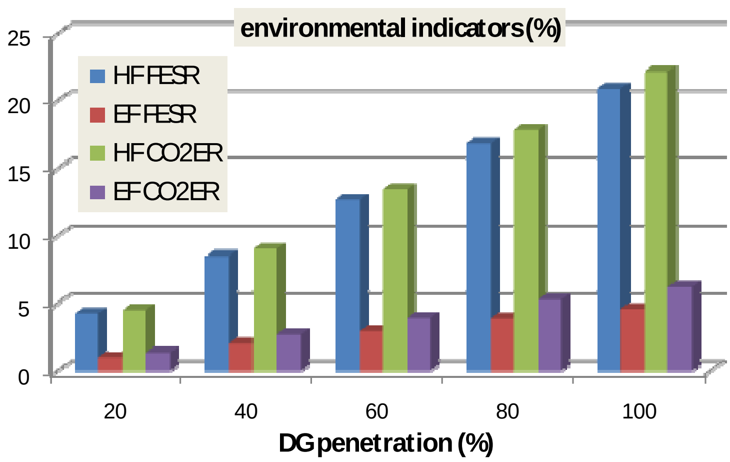


Figure 5.4. Environmental indicators for MG illustrative case study example.

6. Data identification for microgrid assessment and scenario development

This Chapter illustrates the data requirements to run the GDS models for assessment of the impact of microgrids on current network. A large sample of some of the data collected through the GDS template, relevant to generation and demand patterns and scenarios for selected partners, is shown in Annex 2.

6.1 Overview on generic distribution system (GDS) model data

The development of the methodologies outlined in the previous chapters in order to assess microgrid operation and relevant benefits requires the identification of typical distribution networks, in particular for GDS model applications. The utilities and the other partners involved in the project have thus been asked to provide data (at the status quo and for future scenarios) on typical representative distribution networks for their countries. On the basis of the data provided by selected countries, suitable analyses will then be run within TH2.

The data gathering has been carried out in collaboration with WPG. When such data could not be gathered, suitable assumptions are considered in the analysis. In particular, the fractal network generator can be used for general studies and for scenario modelling purposes.

The basic data were requested according to the GDS model template (see Annex 1), and are summarized for the selected countries in Annex 2. Further data are provided within WPG, whereas detailed network data for GDS implementation, although provided for the selected countries indicated, are not explicitly presented.

The relevant information to build up a typical network representative of a GSP connection and simulate its operation over a one-year time span as described in Section 4.2 consists of:

- network topology and structure (possibly including simple single line network diagrams showing typical structure);
- feeder and network component data (overhead lines, cables, transformer, additional technologies, etc.);
- technical system indices (peak load, average losses, etc.);
- loads: (typical profiles for typical segments and seasons, distribution for the different typologies at different voltage levels;
- generation: micro-generation units typically used per country (typology, size, generation profiles for different seasons, including possible intermittency patterns) and distribution of the different typologies at different voltage levels;

- costs (i.e., equipment, maintenance costs, average consumer prices, etc.).

More specific details are given below.

6.2 Data requirements

6.2.1 Network data

For each voltage levels, schematic diagrams or relevant information on the topology of typical circuits connected are necessary (for instance, single line diagrams with busbars, transmission lines, cables, transformers, etc.). According to the GDS data collecting template, this could be synthesized in tables describing the typical modules (and how many) that were connected at and among the different voltage levels.

In addition, the following data on network characteristics and equipment were to be provided:

Transformers (for each module at each voltage level)*:*

- rated voltage (e.g., 20/0.4 kV);
- capacity (e.g., 630 kVA, 7.5 MVA);
- load and no-load active power losses;
- impedance (in Ohm or p.u.);
- voltage regulation (on-load or off-load tap changer);
- max/min voltage variations at substation busbar;
- number of transformer in parallel at the relevant substation:
- minimum breaking power for new switchboards (MVA).

Feeders:

- typical underground (UG) cable, overhead line (OH), and mixed (MX) line characteristics: cross section (mm2), resistance and reactance (Ω/km), capacity (MVA).
- for each circuit in each representative module at each voltage level:
- cross-sections (mm2) (tapered/non-tapered) (e.g. 300 mm2 + 70 mm2);
- type of circuits (OH/MX/UC);
- length (km)
- percentage and characteristics of loads connected to each circuit;
- distribution of load connected along the feeder;
- power factor of the load for each circuit.

Additional information refers to:

Network operation:

- max/min voltage allowed at the end of the circuit;

- ring, meshed, (open-) loop -> in the GDS model, all the networks were supposed to be operated radially, so that non-radial networks were rendered radial through suitable assumptions.

Losses:
- average losses (MWh) in different network levels;
- average fault level (MVA) in different voltage levels.

6.2.2 Consumption profiles and scenarios

In order to address the actual operational characteristics of MG, it is necessary to run simulations based on typical load profiles that resemble the distribution of potential users' agglomerations. Hence, the following load information was requested:
- typical user segments (in case depending on the specific Country) such as residential (with/without electricity heating), industrial, commercial, agricultural, and so on;
- typical normalised after-diversity load profiles, with one-hour average values for weekday, Saturday and Sunday in winter, summer and spring/autumn seasons;
- base load in terms of total peak load in the typical GSP network;
- overall load distribution among voltage levels and percentage distribution among the different user typologies for each voltage level;
- expected load increase rate (%/year).

6.2.3 Generation profiles and scenarios

Micro-generation penetration can represent a variable within the studies of WPH to quantify and qualify the effects of Microgrids (for instance through application of the statistical model in Section 8). However, in order to run sensible analyses with respect to the different power systems involved for selected countries, it is important to know about typical micro-sources currently in use and foreseen to be used. Hence, the corresponding information that was requested through the GDS template entails:

- overall penetration level per country (in GW), for the different generation technologies envisaged (PV, CHP, hydro, biomass, wind, etc.) and for different temporal scenarios (for instance: today, 2015, 2020, 2030);
- penetration level per GSP (in MW), for the different generation technologies and scenarios;
- distribution of each technology per voltage level (e.g., CHP: 70% LV, 25% MV, 5 % HV);
- typical normalized hourly generation profiles for summer, winter and spring/autumn seasons and for typical weekdays, Saturday and Sundays.

Fuel consumption data, assumptions on generation efficiencies and on other characteristics have been carried out on the basis of average figures for units available on the market.

6.2.4 Economic data

In order to address from an economic standpoint the operational and asset-related benefits brought by MG (with respect to the current solutions without microgrids), the following economic information were requested to the partners:

- equipment capital costs (cables, lines, transformers, new switchboards);
- electricity charges for active (€/MWh) and reactive (€/MVarh) energy at the different voltage levels;
- charges for reactive power compensation (absorption and generation) for different voltage levels (€/MVarh/year).

Assumptions on further costs that might be needed, such as cost of implementation of communicational infrastructure needed within MG, according to the models proposed in the other WPs, have been carried out as well. Likewise, cost of implementation of typical generation technologies were taken from average figures available on the market (see also DG1).

6.2.5 Environmental data

Environmental analyses such as primary energy saving owing to cogeneration operation, or CO_2 emission reduction owing to active losses reduction in distribution network (according to the models illustrated in Chapter 5), need information on typical characteristics of conventional energy systems (boilers and power systems) in the various countries. A synthesis of typical values is presented in DG1. When such data were not available, average typical figures for EU countries were assumed.

6.3 Comparison with the networks models analysed in WPG

In WPG typical networks are also used to study the impact of various typologies of distributed and micro-generation technologies, including the assessment of reliability and power quality improvement owing to microgrid deployment. Hence, the relevant data have been collected together with and are consistent with the data needed in WPG. However, whereas the models analysed in WPH refer to *generic* networks, in WPG *typical* specific networks are rather analysed (Figure 6.1).

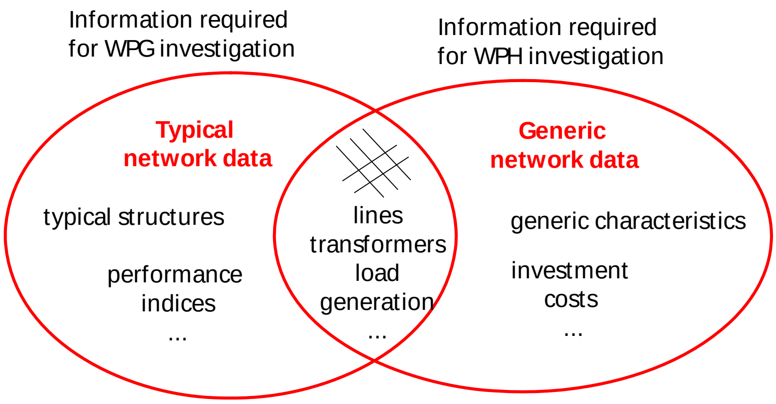


Figure 6.1. Differences between the network data collected in WPG and WPH.

7. Synthesis of data collection for demand/generation scenarios

This Chapter summarizes some of the general data collected in collaboration with WPG and relevant to identify suitable demand and generation scenarios, as well as various characteristics such as environmental performance, network losses, and so on, for microgrid assessment in EU countries.

7.1 Process of data collection

According to what described in the previous chapters, typical networks concerning all distribution voltage levels (HV, MV, and LV) were identified by utilities and partners in each country for the studies relevant to both WPG and WPH:

- INESC Porto in collaboration with EDP has identified typical networks for HV, MV and LV distribution grids, considered as representative for Portugal;
- Lodz-Region Power Distribution Company and the University of Lodz collected data on typical Polish distribution networks, also relevant to the WPH GDS template;
- Data collection in the Netherlands was performed by Continuon, also according to the WPH GDS template;
- The activity of CESI RICERCA has consisted of the collection of typical data and information (where available) about the structure and operation of the Italian MV and LV distribution network;
- NTUA collected information on Greek power supply;
- DTU provided data about a typical Danish Microgrid (Bornholm), which is also subject to further field tests;
- Data collection for Germany, also relevant to the GDS template, was done in collaboration between Siemens and MVV;
- Imperial College, London has provided data from United Kingdom, including GDS models;
- Data on typical Macedonian distribution networks were collected according to the WPH GDS template by the project participants from UKIM and ICEIM-MANU.

Data collection has involved contacts with DNOs, consulting of technical documents, reports and databases (both public and reserved), as well as tight collaboration between WPH and WPG.

7.2 Typical network characteristics and scenarios

7.2.1 Typical network structures

Detailed results of data collection for typical European distribution networks (Portugal, Poland, Italy, the Netherlands, Denmark, Germany, UK, Macedonia and Greece) are provided in Deliverable DG1 of WPG, including simple single line network diagrams for

- 1 typical HV distribution network,
- 2 typical MV distribution networks (Urban MV network, Rural MV network),
- 2 typical LV distribution networks (Urban LV network, Rural LV network).

What is important to point out is that regional differences in terms of network design strategies as well as country peculiarities do actually take place. Indeed, not even typical voltage levels are equal (Table 7.1). This highlights the need for generic analysis tools, besides specific assessment models, such as the network fractal generator described in Section 4.3 and applied for infrastructure replacement profile scenario modelling in Chapter 8. However, reference values for different indices are needed in order to run sensible analyses. The general data provided in the tables below help in this direction. Further details on these and other relevant data are provided in DG1.

Table 7.1. Overview of typical voltage levels in distribution networks in Europe.

	HV [kV]	**MV [kV]**	**LV [kV]**
Portugal	60	30, 15, 10	0.4
Poland	110	15	0.4
Italy	132	20	0.4
the Netherlands	150, 110	50, 10.5	0.4
Germany	110	20, 10	0.4
Greece	150	20	0.4
Denmark	150, 110	60, 10	0.4
Macedonia	110	35, 20, 10	0.4
United Kingdom	132	33, 11	0.4

7.2.2 Typical system losses

One of the major expected benefits from microgrid implementation is the overall decrease in network losses owing to generation being closer to demand points. Hence, as a general comparison reference for the generic analyses run, Table 7.2 summarizes the typical technical losses in Europe for different voltage levels, with average network losses in Europe of about 7%.

It is interesting to point out that the correlation between network losses and country size or population density is relatively weak. This hints that technical losses are primarily dependent on other factors such as network design, operation and maintenance, and so forth. In this respect, to have at disposal flexible analysis tools such as the GDS model and design/analysis tools such as the fractal model developed here represent a major asset for assessment of future microgrid scenario.

Table 7.2. Overview of typical technical losses in distribution networks in Europe.

	HV (%)	HV/MV (%)	MV (%)	MV/LV (%)	LV (%)	total (%)	total (TWh)
Portugal						9.4	4.5
Poland	1.6		7.7		7.7	12.3	14.5
Italy						6.9	21
the Netherlands	0.8		1.0		2.2	4.2	4.5
Germany	0.3	0.6	0.4	1.5	2.6	5.4	29
Greece		0.5	2.7	1.5	1.9	11.6	4.5
Denmark	1.5		1.1		2.2	6.9	2.5
Macedonia	0.04	2.4	1.6	2.4	12.9		
United Kingdom	0.4	0.4	2.9	2.9	2.5	9.1	32.
EU 15						6.8	171
EU 25						7.2	199

7.2.3 General load scenarios

Typical daily load profiles with average values for weekday, Saturday and Sunday in winter, summer and spring/autumn are given for selected countries in Annex 2. Further details on other countries are also provided in DG1. On the other hand, general information on demand levels in the next years are provided in Table 7.3, Table 7.4, and Table 7.5.

Table 7.3. Projected average yearly load increase [%/year] in Europe.

	PT	PL	IT	NL	DE	GR	DK	MC	UK
2008 – 2010	5.15	2	2	2	0.5	3.8	0.5	3	1.1
2010 - 2020	5.15	2	2	2	0.5	2.6	0.5	3	1.1
2020 - 2030	5.15	1.5	2	2	0.5	2.5	0.5	3	1.1

Table 7.4. Projected annual peak demand [GW] in Europe (according to [30]).

	2004	2010	2020	2030
Portugal	9	10	13	16
Poland	21	23	27	32
Italy	54	62	76	91
the Netherlands	17	20	24	30
Germany	77	81	83	-
Greece	9	11	14	17
Denmark	6.3	6.8	6.9	8.0
United Kingdom	67	74	82	84
EU 15	430	474	534	593
EU 25	479	527	596	664

Table 7.5. Projected annual energy demand [TWh] in Europe (according to [30]).

	2004	2010	2020	2030
Portugal	50	59	76	97
Poland	131	136	160	181
Italy	325	366	450	550
the Netherlands	113	129	157	191
Germany	561	572	575	572
Greece	57	67	84	101
Denmark	36	38	41	45
United Kingdom	382	420	469	479
EU 15	2681	2927	3294	3662
EU 25	2973	3249	3673	4089

7.2.4 General generation scenarios

Typical daily generation profiles with average values for winter, summer and spring/autumn were collected for the selected countries for the relevant micro-generation technologies, as described in Annex 2. Further data are also available in DG1.

Table 7.6. Typical current generation characteristics in Europe (according to [30]).

	PT	PL	IT	NL	DE	GR	DK	MC	UK	EU 25
Total gross Generation (TWh/year)	49	162	314	98	637	61	36	6.5	398	3358
Final Consumption (TWh/year)	52	142	340	117	556	56	21.8	8.6	270	2710
Peak demand (GW)	9	21	54	17	77	9	6.3		67	479
Installed capacity hydro (GW)	4.8	2.2	20.7	0.04	10.4	3.1	11.0		4.2	131.1
Installed capacity other renewables (GW)	0.9	0.1	3.3	2.0	19.2	0.5	3.1		2.3	40.5
Total Installed generation capacity (GW)	12.6	31.7	81.5	21.4	129.1	13.1	12.6		81.1	706.5

Regarding RES, the share of specific technologies differs greatly throughout Europe (Figure 7.1), and this could implicate potentially high and different impacts on network operation, as discussed in Section 4.5, with particular reference to power system flexibility requirements and provision. In this respect, Table 7.7 shows a schematic qualitative representation of different regions of Europe according to their conventional generation characteristics [31].

Coordinated control of micro-generation units and controllable loads, according to the models developed within the microgrid framework, could represent an enabling factor to fully exploit the advantages provided by renewable energy sources and clean inflexible generation systems such as CCS, minimizing the network impact and, for instance, potential wind spillage (Section 4.5.2). Some approaches to exploit such potential make use of system aggregation through the concept of virtual power plant (VPP) and other Multi-Microgrids control models widely discussed in WPD.

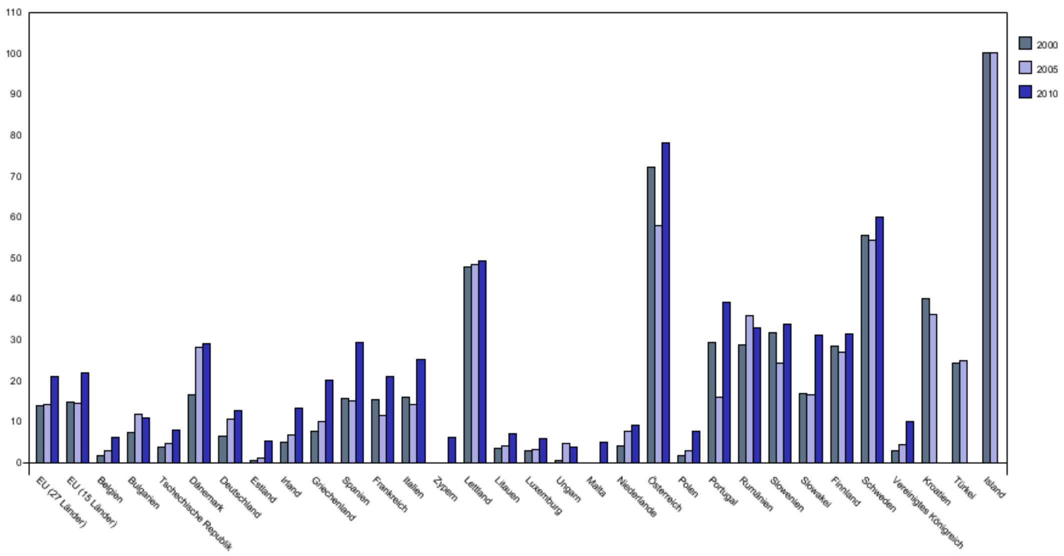


Figure 7.1. Share of Renewables in % of gross energy consumption (source Eurostat).

Table 7.7. Indicative schematic representation of different regions of Europe according to their conventional generation flexibility.

	"South of Europe"	**"Scandinavia"**	**"New member states"**	**"Germany, Austria"**	**"UK"**
Conventional generation flexibility	Low	High	Medium	Medium	Medium

In terms of penetration scenarios, one of the objectives of WPH is indeed to study the impact on energy infrastructures of different levels of microgrid deployment. Thus, the

micro-generation penetration share is typically parameter of the analyses, in order to quantify the impact of MG on network operation, regardless the specific cases.
However, in terms of projections, the development of MG within future scenarios strongly depends on both the benefits that they can provide as well as the possibility of being granted adequate regulatory and political support, as better analysed in Deliverable DH2 and Deliverable DH3. Some general lines for future scenarios are drawn in Chapter 9.

7.2.5 Environmental aspects

Emission factors from fossil-based generation are a function of the generation technology as well as of the fuel itself, as discussed in Section 5.3 and Section 5.4 and further illustrated in DG1. It is important to have reference points to estimate the environmental impact of microgrid deployment. In this respect Table 7.8 summarizes average emission factors per country, while Table 7.9 the total yearly emissions due to electricity supply.
By displacing (fossil-based) centralized generation, efficient low-emission microgrids can decrease the overall emissions from the energy sector. However, as soon as certain power plants are switched off or even phased out due to widespread micro-generation, average emission levels should be recalculated, as discussed in Section 5.3.4.

Table 7.8. Average emission factor (g/kWh$_e$) per country.

g/kWh$_e$	**PT**	**PL**	**IT**	**NL**	**DE**	**GR**	**DK**	**MC**	**GB**
CO_2 equivalent	544	847	457	506	471	689	526	1345	49
SO_2	2.9	5.6	1.6	1.5	2.7	4.3	2.8		2.1
NO_x	1.6	2.8	1.1	1.2	1.5	2.2	1.7		1.3

Table 7.9. Average total yearly emissions per country in Millions of Tons.

Mton/year	**PT**	**PL**	**IT**	**NL**	**DE**	**GR**	**DK**	**MC**	**GB**
CO_2 equivalents	25	133	139	51	292	41	19	6.5	198
SO_2	0.1	0.9	0.5	0.15	1.7	0.3	0.1		0.8
NO_x	0.1	0.4	0.3	0.1	0.9	0.1	0.06		0.5

8. Infrastructure replacement scenario modelling

According to what discussed above, the impact of MG and microgeneration on network infrastructure depends on a number of drivers such as generation profiles, match between demand and supply, penetration of DG, network characteristics, and so on. A suitable and powerful methodology is needed to assess the network value of DG and microgrids, and thus to formulate optimal infrastructure replacement scenarios. Hence, this Chapter presents a general approach based on generic networks to model sustainable network replacement scenarios in the presence of MG. In fact, while the GDS model lends itself well to address the impact of DG and microgrids on actual current power systems, for scenario modelling purposes the fractal model developed enables to draw even more general conclusions to assess the value of MG in terms of infrastructure benefits. A number of parameters can be tuned in, from load densities to number of substations, so that the optimal replacement profiles can be assessed for generic situations as could be encountered in different countries. A major and unique feature of the overall model is that large generic networks can be built by the user, enabling to address system-wise scenarios in generic conditions.

8.1 Generic multi-voltage distribution network model

8.1.1 Generalities on the modelling methodology

Network design practices are an evolving process and are greatly influenced by customer distribution, geographical layout and load density. The addition of local energy systems as MG further complicates the assessment. Such design practices refer to a hierarchical distribution network model that follows the number and the type of the different voltage levels (see Table 7.1). In particular, the optimal number of substations, the types and ratings of the circuits and transformers used, network losses, and reliability performance are amongst the important considerations in designing cost effective and sustainable electrical networks.

In order to capture the benefits of microgrids on a system-wise basis, Imperial has developed a specific methodology to define and assess alternative design strategies that ensure the most cost-efficient solution of distribution networks and thus to model sustainable network replacement scenarios. The methodology is based on assessing how the presence of microgeneration, impacts on the overall investment cost taking into account also the possibility of changing the substation configurations (number and size of substations) besides circuits. Key network performance indicators are thus the minimum number of substations required to meet the load with given quality standards, network cost (infrastructure and loss-related), losses and associated emissions, external costs associated to losses, and so on. In particular, it is important to highlight that starting from network models, the replacement strategies can be assessed according to manifold predefined criteria, including environmental aspects.

In order to evaluate system-wise network replacement strategies, different voltage levels need to be modelled, namely, LV, MV and HV. Indeed, only by modelling the whole distribution cost chain is possible to fully capture the benefits associated to microgrids, even if operating at the LV level only.

8.1.2 Modelling of LV, MV, and HV generic distribution networks

For the LV level, the model adopted is the same as described in Section 4.3.

For MV, essentially the network characteristics are driven by the outcomes from LV network analysis. In fact, assuming that no DG is connected at MV (here we focus on microgeneration and LV microgrids – however, extension to MV microgrids could be carried out as well), this network will supply the MV/LV transformers as well as some industrial customers. However, the load density of LV networks within the MV network varies from region to region. Thus, the MV` network is generated by inputting different sets of LV networks (which can have different load and substation densities) in a so-called *grid-matrix*. The location of MV/LV transformers and their annual loading profiles for each of the MV/LV transformers are recorded in the LV networks and become the input parameters of the MV network. By doing so, the loading characteristics and the main topological characteristics (and spatial distances, in particular) among the MV/LV transformers considered at the LV design stage is kept for the MV network as well. Figure 8.1 illustrates how different LV networks can be 'entered' into an MV network.

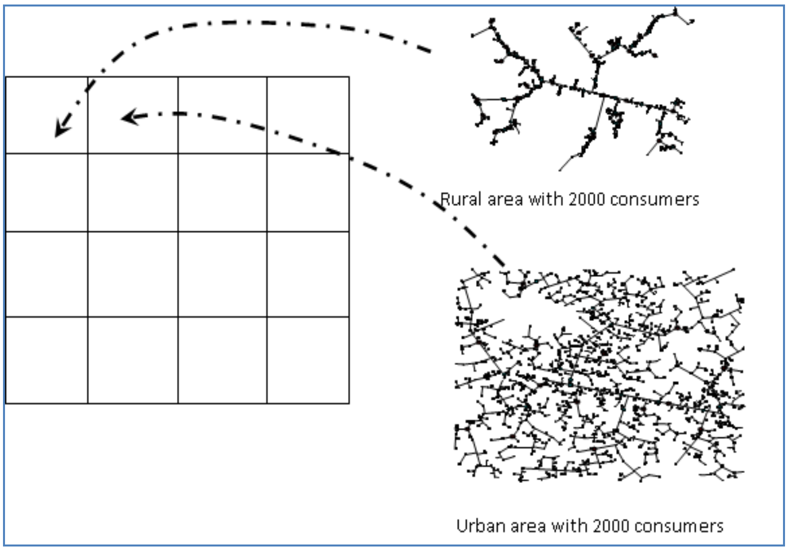


Figure 8.1. Matrix model of MV networks from LV inputs.

The MV "customers" (corresponding to LV substations, mainly, as well as large equivalent loads) are then connected with a controllable branching rate, enabling to

mimic again real network characteristics, as already for the LV case. In particular, it has to be highlighted how it is also possible to take into account the presence of "white spaces" for instance corresponding to parks, green belts, and so on. Figure 8.2 shows an 11-kV MV network (UK case) composed of 65 LV networks, with 15 33/11 kV substations and branching rate equal to 69%. The small 'dots' are 11/0.4 kV transformers (as from LV analysis) and the 'red stars' 33/11 kV transformers.
Depending on the extension of the upstream network, also the next MV voltage level can be modelled through a fractal approach (this can be typically done for countries with four distribution voltage levels as for the UK, Table 7.1). Alternatively, the upper level topology can be modelled in a simplified way, for instance as in the GDS model described in Section 4.2.

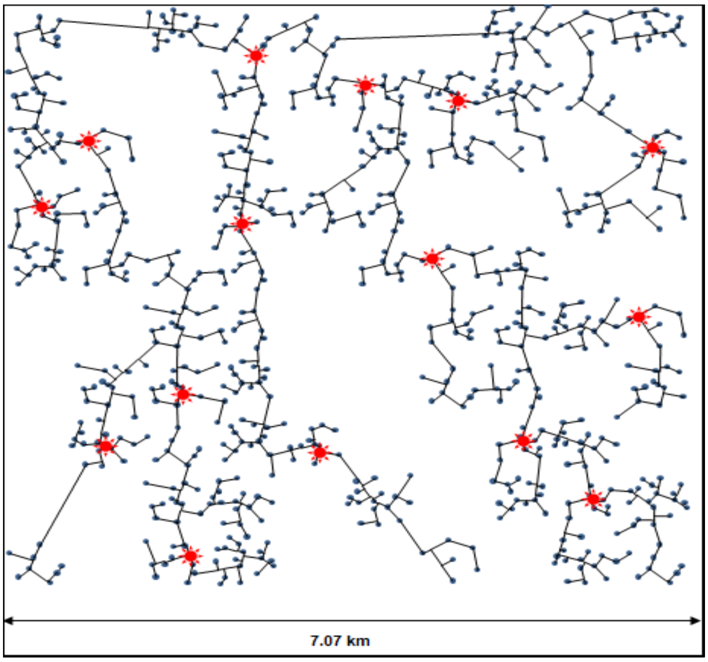


Figure 8.2. MV network with 15 33/11 kV substation (UK case) generated from 65 LV network inputs.

8.2 Network design strategies without and with distributed generation

8.2.1 Network design methodology with no DG

The *base case* replacement scenario contains no DG (and thus no MG), and is to be compared with design scenarios including DG (see below) thus enabling to capture the value of MG.
At LV, the network sizing is carried out on the basis of a minimum LCC methodology, as discussed in Section 4.3, minimising the annualised investment and maintenance cost of equipment and the yearly cost of electricity losses in order to determine the optimal

capacity of the circuits. The investment cost can be for instance annualised over 30 years with 7% rate of return. The minimum LCC approach is adopted for all the voltage levels. Once the network is sized, load flow analyses are run to compute actual network performance and loads at the substation points. The annual loading for the supply points is then recorded to become the input to the higher voltage levels.

Since the design analyses are run here for replacement scenario modelling purposes, the optimal economic design strategy is carried out as a benchmark design to be adopted in the future. However, other design strategies might be adopted as well, such as based on peak design or optimal environmental design [32]. In this respect, it is worthwhile to highlight that with typical energy and component cost, LCC approaches lead to install circuit capacities much larger than the peak loads, above all at the lower voltage levels [7]. This is consistent with the data collected from partners, indicating that distribution utilities tend to replace network assets with larger capacity than from previous design approaches, bringing about stronger networks able to cope with the manifold uncertainties of ever changing scenarios.

8.2.2 Network design methodology including DG

The next step consists of carrying out a network design including DG. The impact of DG will be such that potential reduced flows (at least up to a certain penetration threshold) might imply deployment of smaller circuits. However, DG will also impact on losses, so that the trade-off between optimal circuit investment cost and losses operational costs is to be reassessed. In addition, parametric analyses can be carried out by changing the number of substations at LV as well as upper voltage levels, while the DG penetration level increases. In fact, the presence of lower flows from the bulk power system towards the LV consumers could mean that the optimal design (minimum cost) might be reached by decreasing the number of substations, provided that the supply quality (for instance, voltage requirements) are met in any case.

8.3 Methodology for replacement scenario evaluation

8.3.1 Economic value of microgrids according to network-related cost criteria

In order to assess the network benefits from different microgeneration scenarios, the optimal economic network designed *without* DG is compared with the optimal economic network designed *with* DG. The cost “distance” between the two networks represent the value brought by the microgrid for the considered scenario, and can be used to assess possible replacement design strategies. However, different metrics can be used to assess the value of MG, namely:

- Operational (loss-related) costs: entail the costs associated to losses occurring in circuits and substation transformers (load losses and no-load losses), evaluated on the basis of the economic value of losses.
- Investment costs: entail the annualised costs of circuits and substations.
- Overall network costs: are represented by the sum of operational and investment costs.

Hence, if we indicate with *C* the generic costs for one of the above categories, the relevant evaluation metric (*economic savings*) can be expressed as

$$\Delta C = C - C^{\mu G} \qquad (8.1)$$

where the subscript points out the microgrid case relative to the base case with no DG. The costs as given above yield the value of DG and more in general of microgrids according to the specific metrics. In particular, the overall network cost will be used in the sequel to exemplify the procedure.

All the above cost categories are referred to annual costs (in case normalized with respect to the network peak load so as to allow comparison among different networks), as the LCC methodology used is based on equivalent annual costs, as discussed in [7]. In addition, the relevant cost metrics can also be broken down by voltage level in order to better capture where the benefits actual occur and why.

Also environmental costs could be added to the assessment model, including the energy externality costs associated to energy losses, for instance. Although not related to network aspects, the costs associated with energy generation could be considered too. Further studies in this light are reported in Deliverable DH2 and Deliverable DH3.

On the basis of the metrics defined above, it is thus possible to assess the benefits brought by alternative design strategies for given microgrid configurations. An illustrative example is shown below.

8.3.2 Illustrative example of replacement profile scenarios

In analogy to the example reported in Section 4.3.5, a large UK urban network is considered here to exemplify the replacement scenario modelling introduced. More specifically, the LV network is characterised by the information in Table 8.1, with typical consumer load patterns as illustrated in Annex 2. Different penetration levels of DG are analysed, all based upon 1-kWe Stirling engine micro-CHP and by assuming a typical heat-following load profile as from Annex 2.
In addition, on the basis of the above grid-matrix model, an 11-kV MV network of about 190 km is generated to connect downstream "users" corresponding to each 11/0.4 kV substations as from the generated LV network (Table 8.2) taking into account the LV design scenario with DG and without DG.

In fact, for the LV network design with different DG penetration levels, two approaches have been considered:

- Component (circuit and transformer) design without taking into account the flows generated by DG;
- Component design taking into account the DG production.

Concerning the component design at 11-kV (with no DG assumed to be connected), the two LV design approaches lead in practice to the same MV design. In fact, the power flows from LV, on which the MV network is designed, do not practically differ in the two cases apart from a minor change in losses occurring due to the different LV circuit sizing. However, although the downstream flows are fixed, different number of 11-kV substations is also considered in the analysis, namely, fixing the number to the optimal base case with no DG (13), and then by changing the number of 11-kV substations heuristically searching for an economic minimum while the LV design changes due to the presence of DG.
The same reasoning is developed for an upstream 33-kV connected to the 11-kV one, with a base case of 5 substations (that may also be optimally decreased with DG penetration) and an overall length of about 29 km.

A synthesis of the results is shown in the figures below. It has to be noticed that in assessing the investment cost only the cost of equipment has been considered, without excavation costs. Such costs might be substantial in urban case. However, excavation costs would be roughly the same for all the scenarios considered, so that in comparative assessment would cancel out.

Table 8.1. Characteristics of the LV network used for network assessment illustration.

Number of consumers	2000
Peak demand [MVA]	4.9
Total number of 11/0.4kV substations	
Annual Consumption [MWh/year]	19355
Load density [MVA/km^2]	4.9
Substation density [Nsub/km^2]	10
Network area [km^2]	1
Total network length [km]	28.2

Table 8.2. Characteristics of the 11-kV network used for network assessment illustration.

Total number of LV consumers	150000
Total number of 11/0.4kV substations	750
Peak demand [MVA]	377
Annual Consumption [MWh/year]	1,472,502
Load density [MVA/km^2]	3.8
Substation density [Nsub/km^2]	0.13
Network area [km^2]	100
Total network length [km]	189.5

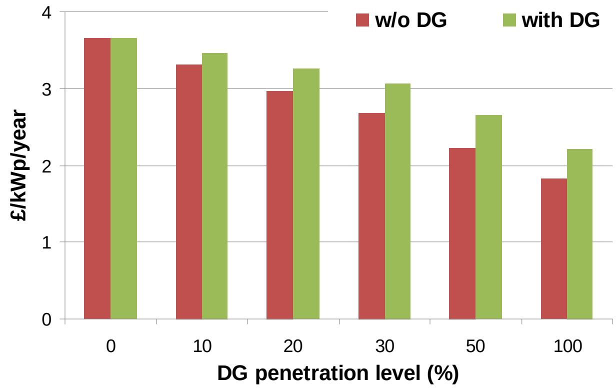


Figure 8.3. Cost of losses (for circuits and transformers) for the sampled LV network for different DG penetration levels.

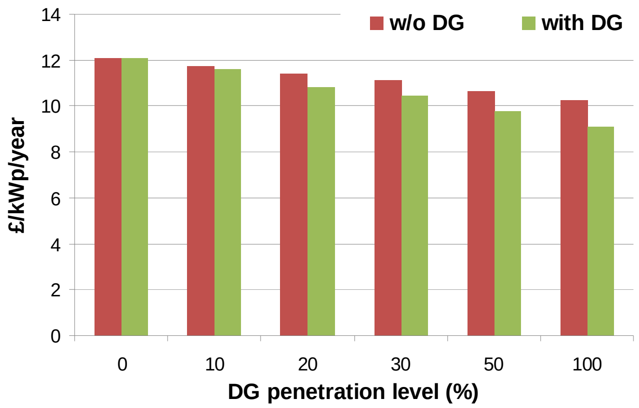
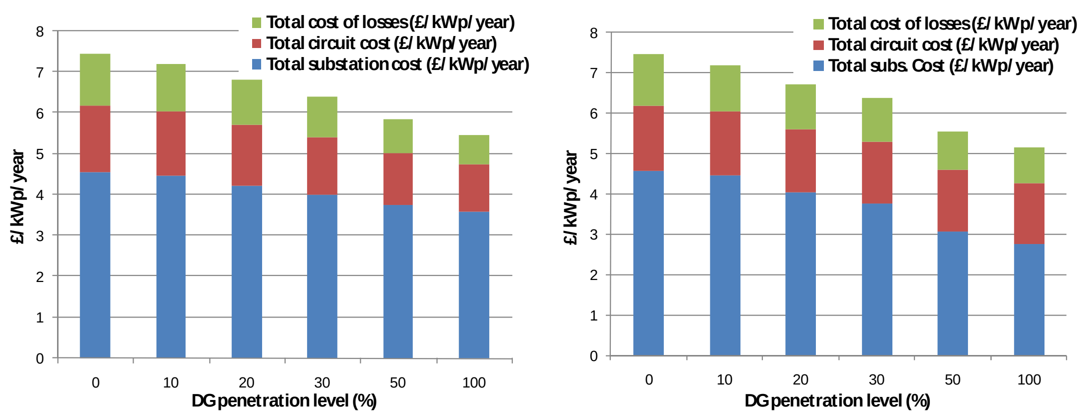


Figure 8.4. Total cost (losses and investment cost of circuits and transformers) for the LV sampled network for different DG penetration levels.



a) b)

Figure 8.5. 11-kV cost with: a) fixed number of substations; b) variable number of substations.

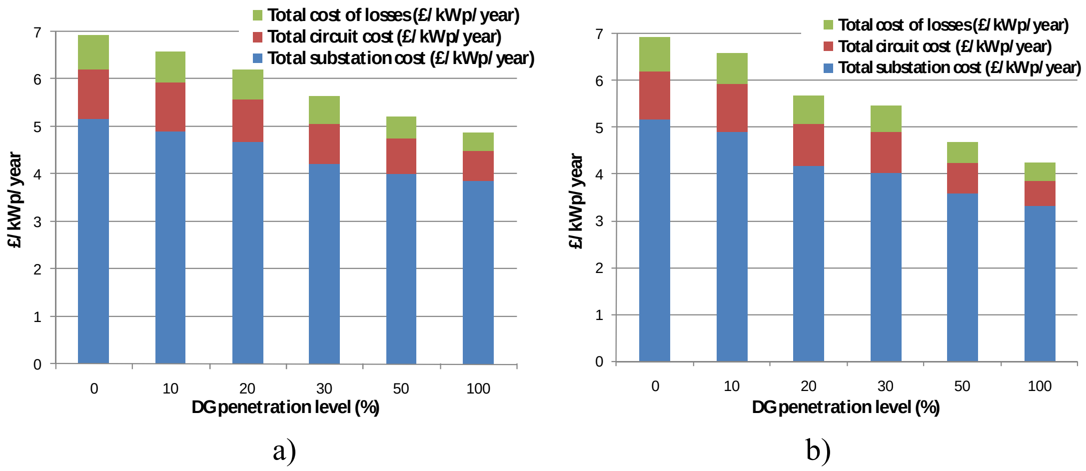


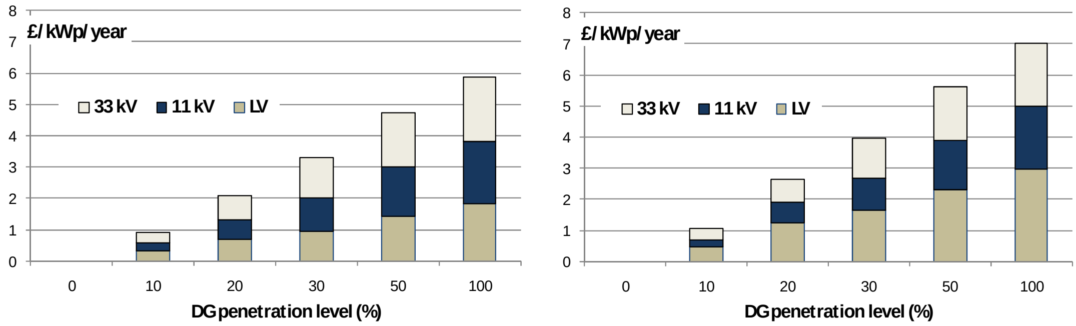
Figure 8.6. 33-kV cost with: a) fixed number of substations; b) variable number of substations.

8.3.3 *Discussion on the case study results and on the infrastructure replacement scenario model*

From the results in Figure 8.3 indicating the cost of losses at LV, it is apparent how losses decrease with the penetration level, mainly owing to the positive correlation between DCHP production and loads. However, it is interested to notice that when the network is designed taking into account the flows generated by DCHP, losses are higher. In fact, being the equivalent circuit flow smaller, smaller capacity can be used to size circuits and transformers while looking for the overall economic optimum. This is confirmed by Figure 8.4, where the overall network cost (for components and losses) is plotted. Now, when the design is carried out with DG, the overall cost is always smaller than when the network is designed not taking into account DG, in spite of the above higher losses.

Same types of analyses are shown in Figure 8.5 and in Figure 8.6 for the 11-kV and 33-kV network, respectively, with the cost breakdown between losses and components (circuits and transformers for the latter), and for fixed and variable number of substations. The results show that the component cost, above all for substations, is dominant for both MV networks. Also at LV the equipment cost is predominant, but the weight of losses is relatively higher than at MV, as expected. Also, there is a potential to decrease the overall cost while DG increases by decreasing the number of substations. However, the impact is more apparent for larger penetration and is not substantial. In addition, it has to be considered that, although not quantified here, higher number of substation generally means higher reliability level.

The above results allow a straightforward assessment of the value of microgrids in distribution network replacement scenarios. In this respect, Figure 8.7 shows the value of DG on the network design in the case of fixed number of transformers in the MV networks. It can be appreciated that the value of DG increases substantially with the penetration level, as more asset can be saved in the MV networks. In addition, if also the LV network is designed taking into account the contribution of DG, the overall networks savings can be even higher.



a) b)

Figure 8.7. Value of DG for different penetration levels and fixed number of transformers: a) LV network designed without DG; b) LV network designed with DG.

As general comments on the results and on the methodology developed, it must be considered that in this example, aimed at illustrative purposes only, *uncontrolled* CHP systems have been considered. This situation could occur at the initial stage of DG penetration. It is expected that the possibility of controlling DG within microgrids will indeed bring much higher network benefits, as illustrated in the example in Section 4.3.5. This issue is also intrinsically related to the benefits that DG (controllable or not) can bring on networks in dependence on the correlation between demand and supply. Indeed, although this aspect is intuitive and qualitatively straightforward, it needs to be investigated systematically in order to capture actual benefits for different countries and set out the direction for microgrid evolution. This will be carried out in Deliverable DH2, where similar analyses to the UK case study will be run on the basis of the data gathered for addressing network replacement profile scenarios in European countries.

9. Microgrid evolution roadmap

On the basis of the models and the information discussed in the previous chapters, this Chapter discusses the role of microgrids in the evolving power and more in general energy systems in the next years. More specifically, after discussing the flow exchanges occurring between microgrids and the "classical" network at different voltage levels in future scenarios, the key role of controllable microgrids to increase the system flexibility is highlighted. Then, a roadmap for microgrid evolution is shown, backed by demand and supply scenarios that could characterize the EU power systems in the next couple of decades. In particular, it is pointed out how microgrids with controllable DG and loads are likely to represent enabling solutions to design and operate the power systems of the future. In particular, microgrid benefits will be substantial in the light of an expected "electrification" of other energy sectors such as heating/cooling generation and transportation and of decreasing level of generation flexibility boasted by large-scale low-carbon plants such as based on RES, nuclear and CCS technologies. Further than that, the presence of a large amount of dispersed controllable loads and generation, with possibility of generating locally other energy vectors such as heat and cooling from absorption chillers, will allow a more economic and efficient design of the overall energy infrastructure, paving the way to microgrid-based integrated energy systems.

9.1 Interaction between microgrids and power system

9.1.1 Energy flow interaction

From the considerations in the previous chapters, there are a number of intertwined issues that could determine the potential evolution of MG. In particular, it has to be pointed out potential pros and cons as seen in today's framework should be revisited with the evolution of the power system. Suitable evolution and evaluation models are needed to address the change of impact from microgrids on the power system over the years. Considering the current and potential future characteristics of MG and power systems as structured in most countries, their interaction is summarized in Figure 2.1.

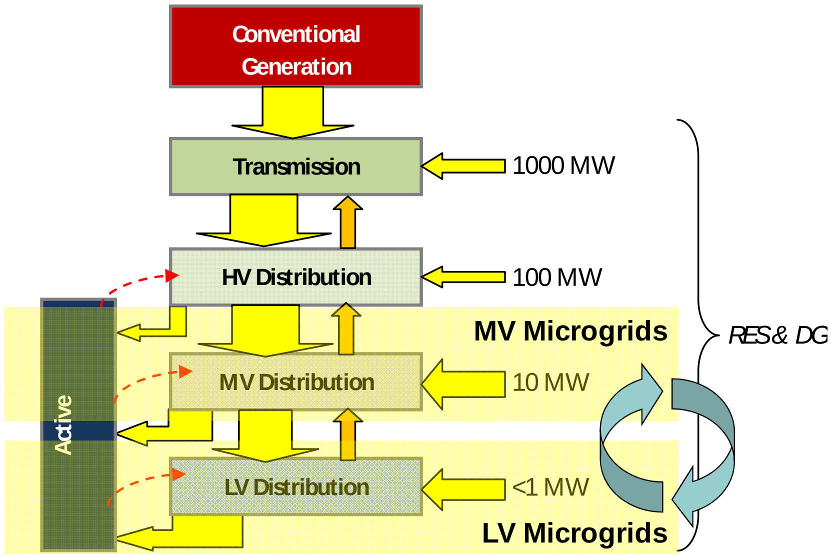


Figure 9.1. Schematic flows and interactions in a microgrid-based scenario.

With respect to Figure 2.1 schematizing the classical power system features, Figure 9.1 illustrates a completely different energy flow configurations. In particular, a major amount of energy is produced at the MV and LV distribution level within MG, while DG technologies also produce energy at sub-transmission and transmission levels. In addition, owing to DG counter-flows among voltage levels may now occur, in contrast to classical unidirectional flows from generation towards the final consumer. The specific set of DG technologies to be adopted is of course likely to reflect the type of network they are included in (for instance, micro-hydro technologies are more likely to be developed in rural areas), as well as the potential related to geographical configurations (for instance, PV systems are more likely to be effectively installed in Southern countries).

At the distribution level, MG would impact on the network in terms of decreasing losses and improving voltage profiles up to a certain extent of penetration level of DG. For relatively larger penetration indices, potential negative impacts (voltage rise and voltage increase) could be mitigated by AM operation and DSM. Likewise, the major effect on the transmission system would refer to decreasing the line flows and potentially decongest the lines (effect on losses is likely to be less significant, also due to the already small contribution of transmission losses out of the overall power system quota).

9.1.2 Virtual Power Plant (VPP) modelling

Regarding more specifically MG architectures, microgrids are envisaged to operate at both an LV level and an MV level. In fact, in order to maximize the benefits from MG, LV MG aggregation is envisaged at the MV level, thus enhancing "visibility" of DER at the grid upper levels, leading to the so-called Multi-Microgrid approach developed within this Project (see in particular WPD). More specifically, such an aggregation could be carried out either for technical reasons (provision of ancillary services, for instance), or for economic reasons (trading with the energy markets), or for both. In this direction, the concept of VPP [33][34] entailing Multi-MG can be a suitable means to model MG technical and economic interaction with network upper levels. According to this concept, generators can be dispatched within MG, and in turn LV MG are dispatched within multi-MG at MV level. This mutual interaction explains the arrows in Figure 9.1 between LV and MV, occurring through VPP-oriented control strategies carried out by MG and multi-MG central controllers on the basis of technical or market criteria (see WPD for details).

9.1.3 Active role of demand

Another major feature highlighted in Figure 9.1 is the presence of "*feedback arrows*" from the demand block to the network. Indeed, together with controlled distributed generators, also intelligent loads will play a certain role within the MG paradigm, within the broad field of application of DSM [34]. In this respect, AM can be seen orientated to both generation and demand. For instance, insufficient local generation due to temporary scarcity of natural resources or generation failures might be coped with through load-shifting actions or utilization of power stored in storage systems, if energy withdrawal from the upper grid is to be avoided (for instance, to manage congestions in the transmission network). On the other hand, generation in excess of local demand rather than be injected in the upper grid (for instance because it would cause high losses or voltage rise) could be used to recharge storage systems, in case in the form of other energy vectors such as heat (for instance through heat pumps) and, in perspective, hydrogen. In general, it can be envisaged that with increasing deployment of DG together with intermittent and uncontrolled RES and low-carbon inflexible CCS or nuclear plants (Section 4.5) in distribution networks the role of active demand to provide further dispatching options will increase. In this outlook, the concept of VPP illustrated above with specific focus on generation within MG can be extended to entail also controllable loads. Hence, the dispatching algorithms carried out by the centralized MG or multi-MG controller should take into account both DG and demand.

The need for simultaneous local generation and load dispatching is likely to become more crucial with the increase of electrical loads related to heating/cooling generation and transportation. In fact, new energy solutions related to complementary energy sectors such as *heat generation* and *transportation* might exacerbate the criticality of developing suitable DSM options. In particular, shifting towards electricity-based heating systems adopting heat pumps are viewed as one of the most promising approaches to GHG reduction while the generation mix becomes more and more decarbonised. For the same reasons, adoption of electric vehicles deploying low-carbon electricity (for instance, recharging batteries during the night, thus also allowing load factor increase for the overall generation system) is lately arising as a viable option to decrease the environmental burden of the transportation sector. However, widespread implementation of electricity-based heating and mobility will imply a substantial load increase at the distribution level. Hence, adoption of these options needs to be adequately supported through suitable control strategies, in order to avoid exacerbating balancing issues from intermittent loads (see also Section 4.5), possible congestions in distribution networks, and the need for substantial enhancement of the circuit capacity to carry the new flows. In this respect, it has also to be considered that local generation in the presence of skyrocketing loads might be seen as a compulsory solution to optimize future network design while economically minimizing the plant capacity to be installed, according to the replacement models developed in Chapter 8.

9.1.4 Major trends of microgrids impact on centralized generation

From a generation perspective, it appears crucial to consider the potential evolution of the centralized mix in order to address the relevant impact due to MG. More specifically, although of course the generation mix is very specific to the single countries, in general the following trend milestones can be pointed out in those power systems dominated by thermal power plants:

- *Current generation scenarios*: DG in microgrids is displacing relatively low-efficiency marginal technologies with high-efficiency low-carbon sources (CHP or RES). The penetration of DG is generally limited, no major hurdles to further diffusion appear yet, microgeneration at a distribution level is treated as negative demand.
- *Likely scenarios in the next years*: a number of low-carbon centralized and large-scale technologies come up (wind, mainly, and potentially nuclear plants); microgrids will displace the marginal thermal power plants, that is, the least-efficient and highest-pollution units within the updated generation sets, that now already include a considerable share of GTs, CCGTs, RES, and so on. The average generation efficiency and CO_2 emission factor are greatly improved with respect to the current situation.
- *Future scenarios*: typical MG operation might displace relatively high-efficiency thermal plants; CCS systems are likely to occupy a certain share of generation, exacerbating the flexibility issues brought about by high penetration of uncontrollable renewables. MG are likely to be dispatched through equivalent aggregation made visible to the transmission network through VPP models, and substantial MG value is now related to flexibility services provision.

9.2 Roadmap for microgrid evolution

Although scenario formulation is in general highly subject to intrinsic uncertainty, the targets set by the European Commission and local Governments, as well as recently by the USA, in terms of GHG reduction and energy efficiency are likely to convey towards a future characterized by larger presence of RES and low-carbon technologies (such as nuclear or CCS systems) than today. In addition, different networks will witness diffusion of different technologies encompassing complementary sectors other than electricity, such as heating/cooling generation and transportation, also depending on the economic profitability and policy indications in each specific country.

In any case, on the basis of the above discussions MG role will be on the one hand to contribute to integration of RES and CHP at distributed levels, and on the other hand to increase the system flexibility in response to increasing penetration of large-scale intermittent or inflexible sources (Section 4.5) as well as demand associated to other sectors (Section 9.1.3).

On the basis of the above discussions, possible supply/demand scenario evolutions in the EU in the next two decades are reported in Table 9.1. Of course, the scenarios are to be considered as roughly indicative of potential trends, while the actual implementation of DG penetration and relevant technology mix, conventional generation mix, heating and transportation options based on electricity, and so on, is country-specific and cannot be foreseen. In spite of this, scenario formulation allows the establishment of likely frameworks within which MG assessment analyses can be carried out.

In Table 9.1, DG penetration levels refer to potential deployment of DG systems in distribution networks, to be operated within MG. The focus is set on DCHP, larger CHP and PV, the most likely technologies to be deployed. However, also micro-wind and micro-hydro could roll out in specific conditions. In particular, it is possible to envisage a predominance of CHP systems in northern countries, while for southern countries PV will play a substantial role, with CHP still likely to be deployed anyway also to potentially exploit its controllability. Hence, while CHP share could increase in the future to increase flexibility in southern countries, in northern countries PV might increase its share with conversion efficiency improvement. In addition, although currently peaks in northern countries typically occur in winter, the increasing share of air conditioning might lead to shift the peak demand to summertime periods. Hence, larger PV deployment could be envisaged to exploit the correlation between weather conditions and demand. Intermediate situations could occur in central regions of Europe.

The decrease in conventional generation flexibility indicates a likely increase in large uncontrolled RES (wind, in particular) and deployment of less flexible conventional generation such as nuclear and, in perspective, thermal plants equipped for CCS. Subsequently, also the average emission factor from the bulk energy production system is envisaged to decrease, also in the direction of meeting the stringent Kyoto's Protocol commitments.

Finally, three load variations scenarios can be typically envisaged, with a base case of load growth indicated as BAU, while a low-growth scenario might correspond to implementation of efficient DSM strategies. However, also a high-growth scenario needs to be considered, corresponding to widespread adoption of reversible electric heat pumps and electrical vehicles set out to exploit a more and more decarbonised generation mix.

Table 9.1. Evolution scenarios for Microgrids and power systems.

		2010	2020	2030
DG penetration in microgrids		10%	20%	30%
CHP/PV share in EU regions	***North***	95/5%	90/10%	85/15%
	Central	60/40%	55/45%	50/50%
	South	20/80%	25/75%	30/70%
Conventional generation flexibility		medium/high	medium	medium/low
Average CO_2 emission factor variation		0	-20%	-50%
Load variation	***low***	0	+10%	+20%
	BAU	0	+30%	+50%
	high	0	+50%	+100%

Starting from and complementarily to the supply/demand scenarios in Table 9.1, the following stages of MG evolution can be envisaged:

- *Infancy level*: at this stage, which corresponds with today's situation, various small-scale technologies are starting being connected to LV networks, namely, micro-CHP Stirling engines and cogeneration MTs, ICEs, and PV systems. Such technologies are controlled according to simple predefined strategies such as thermal load-following (DCHP case), or by the local operator with logic of profit maximization or cost minimization while supplying the local load. The impact on distribution networks is not significant owing to the relatively small penetration. Demand is still "passive", although smart metering systems and high-tech ICT are starting to be installed, allowing bi-directional information flows with the network operators.
- *Development level*: further generation and enabling technologies arise, such as larger CHP (MTs, ICEs, FCs) with DH and district cooling (absorption chillers can be used for high efficiency trigeneration applications [28][29]), in case connected to MV networks, small-scale wind generators connected to both LV and MV, hydro-generators connected to both LV and MV, reversible electric heat pumps for green heat/cooling generation, and so on. In particular, while electricity-based heat generation and air conditioning brings about substantial load increase, the presence of local generation mitigates the need for network expansion. Smart metering is widespread, and DSM can be carried out (targeting, in particular, controllable electricity-based heating/cooling systems) owing to the presence of an adequate ICT infrastructure. Distribution network are designed taking into account the presence of distributed generation and controllable loads. In particular, an optimal mix of distributed CHP of various scales and electrical heating/air conditioning can be

sought in the attempt to optimize environmental benefits together with network design.

- *Establishment level*: with increasing DG penetration, AM is required to accommodate further DG avoiding network upgrade costs. At the same time, the DG units can be coordinated within MG in order to comply with various requirements (at also for upstream networks) including voltage regulation, frequency response, and so on. Electrical vehicles are likely to become a more and more widespread option. Hence, while local generation mitigates the network flows, DSM strategies become crucial to manage the grid load and mitigate balancing issues while the conventional generation becomes less flexible.
- *Maturity level*: microgrids are widespread and visible as single entities to the upstream grid. In addition, multi-MG can be set so as to enhance the visibility at the transmission level and interact with centralized markets. In this respect, models such as VPP play a major role in terms of aggregation. Visibility is also needed at the transmission level in order to provide flexibility services from controllable loads and DG in response to increasing penetration of intermittent and inflexible centralized generation. Microgrids are now basically operated as *integrated energy systems*, where a number of energy vectors such as gas, electricity and potentially hydrogen are optimally generated (locally or remotely) and dispatched to supply manifold responsive and controllable loads such as reversible heat pumps, electric vehicles, and so on. District energy systems for heating and cooling may be used as sinks to distribute the cogenerated vectors and increase the overall generation efficiency of distributed multi-generation energy systems [36]. Clear operational benefits arise from the integrated management of multiple energy vectors. The transportation and distribution infrastructure of the different energy vectors (with a predominance of electricity) are also optimally designed in an integrated fashion.
- *Microgrid-based integrated energy systems*: at this stage, there is no distinction between distribution networks and MG, now being the grid completely "smart". The impact of this new configuration is now to be addressed according to different methodologies, as losses, environmental impact, infrastructure deferral benefits, and so on, are all to be referred to new integrated design strategies. The flexibility provided by MG represents now a major benefit. New models are needed to design electricity networks integrated to the infrastructure relevant to the other energy sectors in the presence of distributed multi-generation energy systems.

This *microgrid evolution roadmap* is synthesized in Table 9.2, covering a time span equivalent to about twenty years, up to 2030.

The issues discussed are also graphically represented in Figure 9.2 [37], illustrating the evolution of the power system characteristics according to the microgrid roadmap in terms of infrastructure capacity (networks, centralized generation and DG) and control logics. In particular, the stage of the Business-As-Usual (BAU) future is likely to occupy the next ten years, while the full development of modern power systems with microgrids and active networks is likely to occur towards the end of the MG evolution timeline developed. Passing from the BAU case to the "active" future will be the ultimate step for microgrid integration, when all the benefits from distributed controllability in terms of network congestion relief, reduced network infrastructure need, increased flexibility for balancing issues, increased energy and environmental efficiency, and so on, will fully arise.

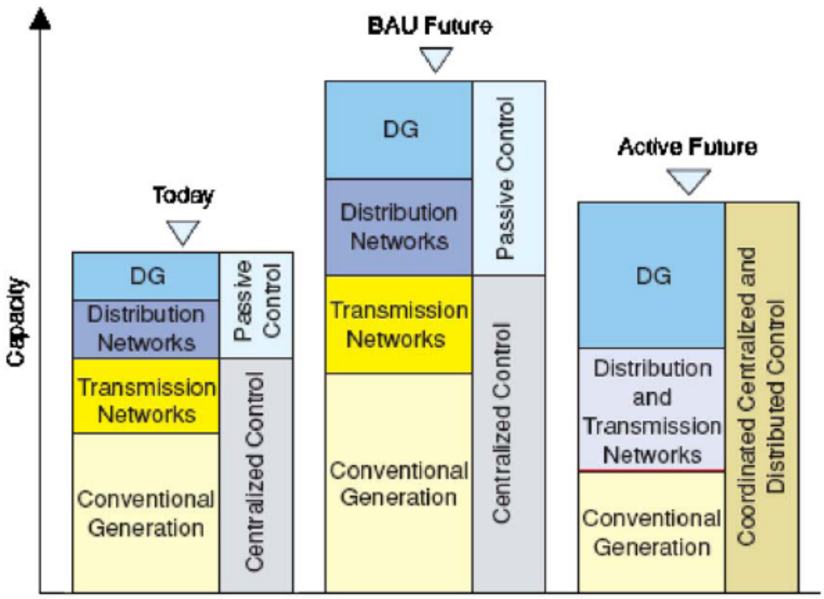


Figure 9.2. Power system infrastructure evolution (source [37]).

Table 9.2. Roadmap of evolution and role of microgrids within power systems.

<table>
<tr><th></th><th><2010</th><th>2010</th><th>2015</th><th>2020</th><th>2025</th><th>2030</th><th>>2030</th></tr>
<tr><th>Stage</th><th>Infancy</th><th colspan="2">Development</th><th colspan="2">Maturity</th><th colspan="2">Full integration</th></tr>
<tr><td>Equipment</td><td>Current limited level of DG at LV: micro-CHP, MT, PV</td><td colspan="2">Additional DG penetration at LV in hot spots, mostly driven by economic reasons (CHP, in case backed by incentives);
regulatory back-up for RES (PV, mainly)</td><td>Electrical vehicles become widespread</td><td></td><td colspan="2">After replacement deferral, infrastructure to be replaced (aging, RES penetration, etc.);
distribution systems based on MG/Multi-MG</td></tr>
<tr><td></td><td></td><td colspan="3">CHP with heating and cooling networks (MV); trigeneration;
small-scale wind (LV, MV);
small-scale hydro (LV, MV);
controllable loads for heating/cooling</td><td></td><td></td><td></td></tr>
<tr><td>Market</td><td></td><td colspan="3">Market interaction with upstream grid and centralized generation;
DG aggregation and market interface</td><td></td><td></td><td></td></tr>
<tr><td></td><td></td><td></td><td colspan="4">Market model enhancement through VPP;
controllable DG, DSM, AM in MG;
multi-microgrids interacting with each other and with external markets through VPPs;
interaction with transmission system</td><td></td></tr>
<tr><td>Infrastructure Impact/Role</td><td></td><td colspan="4">DG/RES increase calls for requirements for generation and load local centralized controllability through smart metering, DSM, active management;
microgrids internal markets for resource dispatch; impact <u>on</u> centralized generation scenarios -> conventional generation (thermal, large RES) changes (higher efficiency, peaking plants, old plants displaced, etc.)</td><td></td><td></td></tr>
<tr><td></td><td></td><td></td><td colspan="4">Impact of centralized generation scenarios on benefits brought by MG (energy, emission, losses, security, to be rethought in part);
“updated” role of MG -> major driver: controllable MG as a key tool to manage large RES penetration and more inflexible mix with nuclear and CCS; microgrid “active” role increasing with the years, with the need for a more active network (DSM and AM), rather than for “spot benefits”; MG are operated and designed together with other infrastructures relevant to other energy vectors; integrated energy systems and distributed multi-generation</td><td></td></tr>
<tr><td>Research</td><td>Studies on drivers for change</td><td colspan="2">System-wise impact analyses for network (losses, infrastructure deferral, reliability, etc.) and for energy, environmental and economic benefits</td><td></td><td colspan="3">New distribution system design: optimal circuit design including DG, DSM, AM, and so on;
conventional generation has changed; transmission system to be reconsidered with RES, CCS and MG; CBA analysis</td></tr>
</table>

10.Conclusions

This report has described the results of the investigations performed in WPH, Task 1 of the *MORE MICROGRIDS* Project.

After describing the main features of current centralized power systems and some of the forces concurring to their changes, the drivers towards more decentralized energy systems and the role of microgrids within the evolving framework have been discussed.

A set of methodologies and models to address the impact of microgrids on network structure and operation have been formulated and illustrated. The objective is to develop suitable tools to estimate the global benefits resulting from microgrid integration in current and future power systems. The methodologies formulated address infrastructure investment costs, operational costs, energy efficiency, environmental impact and environmental costs, and so on, and allow comprehensive analyses of the impact of microgrids in power systems. In particular, the network tools developed are flexible enough to be applied in generic scenarios and allow system-wise assessment of microgrids. Based on the models developed, a methodology for optimal network replacement profile scenarios has also been formulated and illustrated. Hence, the benefits from microgrid installation and operation in future networks can be clearly outlined, so that network operators and decision makers can rely on a solid support to set out the direction of evolving energy systems.

In order to have benchmark starting points to assess the impact and the benefits of microgrid scenarios, relevant information has been collected on network characteristics and demand and supply scenarios from the partners. The data gathered will be used to tune the parameters of the models developed to run sensible studies. In addition, on the basis of the collected information, of general assumptions, and of extended investigations supported by results from the models developed, a general picture of the potential evolution of microgrids has been described. More specifically, a *microgrid evolution roadmap* has been drawn, illustrating the likely potential role of microgrids within European power systems in the next decade consider a number of possible scenarios.

Building up on the information gathered, the scenario formulated and the tools and methodologies developed, systems-wise assessment analyses of technical, economic and environmental Microgrid benefits at different levels will be carried out. The results will be illustrated in Deliverable DH2 and Deliverable DH3.

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Annex 1 Network Data Requirements for the GDS model

In this Annex a schematic representation of the tables in the GDS template that the partners were required to fill in (the specific case refers to Poland) is provided. Detailed representation of the connection of the different modules with each other, and of the distribution of DG and loads along each circuit in each module, have also been provided by selected countries.

Load Data per GSP

Total Maximum Load (MW)	
Percent of Max load connect at 0.4kV network	
Percent of Max load connect at 15kV network	
Percent of Max load connect at 110kV network	

Ratio of various load types (%) at 0.4kV network	
domestic without electric heating	
domestic with electric heating	
industrial	
commercial	
Agriculture	

Ratio of various load types (%) at 15kV network	
domestic without electric heating	
domestic with electric heating	
industrial	
commercial	
Agriculture	

Ratio of various load types (%) at 110kV network	
domestic without electric heating	
domestic with electric heating	
industrial	
commercial	
Agriculture	

Load Increase Rate (%/year)	

Load Power Factor at different voltage level	
0.4kV	

15kV	
110kV	

Typical Days Length (days)	
winter weekdays	
winter saturdays	
winter sundays	
Spring/Autumn weekdays	
Spring/Autumn saturdays	
Spring/Autumn sundays	
Summer weekdays	
Summer saturdays	
Summer sundays	
Total	

Total number of GSPs	

DG Data

Total DG installed capacity (in Country)

Type	level 1 (MW) - today	level 2 (MW)	level 3 (MW)	level 4 (MW)
Offshore Wind				
Onshore Wind				
Micro CHP				
Small CHP				
Medium CHP				
Large CHP				
PV				
Biomass				
HydroGen				
Landfill Gas				
Industrial Waste				

DG penetration levels (per GSP)

Year	2008	2010	2020	2030
Type	level 1 (MW) - today	level 2 (MW)	level 3 (MW)	level 4 (MW)
Offshore Wind				
Onshore Wind				
Micro CHP				
Small CHP				
Medium CHP				
Large CHP				

PV				
Biomass				
HydroGen				
Landfill Gas				
Industrial Waste				

For each penetration level		Percent of installment among different voltage level(%)		
Type	Max Capacity/GSP(MW)	0.4kV	15kV	110kV
Offshore Wind				
Onshore Wind				
Micro CHP				
Small CHP				
Medium CHP				
Large CHP				
PV				
Biomass				
HydroGen				
Landfill Gas				
Industrial Waste				

Transformer Data

Tap Changer State at 0.4kV Tx	
Max voltage drop/rise Limit(pu) at substation 0.4kV busbar	
Tap Changer State at 15kV Tx	
Max voltage drop/rise Limit(pu) at substation 15kV busbar	
Tap Changer State at 110kV Tx	
Max voltage drop/rise Limit(pu) at substation 110kV busbar	

General network constraints

Max voltage drop/rise Limit(pu) at the end of 0.4kV ciruit	
Max voltage drop/rise Limit(pu) at the end of 15kV ciruit	
Max voltage drop/rise Limit(pu) at the end of 110kV ciruit	

Energy costs

Q compensator Generation cost at 0.4kV(€/Mvar/Year)	
Q compensator Absorbtion cost at 0.4kV(€/Mvar/Year)	
Q compensator Generation cost at 15kV(€/Mvar/Year)	

Q compensator Absorbtion cost at 15kV(€/Mvar/Year)	
Q compensator Generation cost at 110kV(€/Mvar/Year)	
Q compensator Absorbtion cost at 110kV(€/Mvar/Year)	

Electricity charges at 0.4kV(€/MWh)	
Reactive Power charges at 0.4kV(€/MVarh)	
Electricity charges at 15kV(€/MWh)	
Reactive Power charges at 15kV(€/MVarh)	
Electricity charges at 110kV(€/MWh)	
Reactive Power charges at 110kV(€/MVarh)	

Switchboard costs

Voltage level	New switchboard minimum break rating (MVA)	New switchboard capitalised cost (€)
220/110kV		
110/15kV		
15/0.4kV		

Example of normalised daily load profiles

Customer type	Season	Period	hour		
			1	---	24
Residential load without electric heating	Winter	Weekdays			
		Saturdays			
		Sundays			
	Spring/Autumn	Weekdays			
		Saturdays			
		Sundays			
	Summer	Weekdays			
		Saturdays			
		Sundays			

Example of normalised daily load profiles

Customer type	Season	Period	hour		
			1	---	24
Offshore Wind	Winter	Weekdays			
		Saturdays			
		Sundays			

	Spring/Autumn	**Weekdays**			
		Saturdays			
		Sundays			
	Summer	**Weekdays**			
		Saturdays			
		Sundays			

Example of module connection topology information

Voltage level	0.4kV	15kV	110kV
Nb of model type	6	4	1
Nb of each model type per GSP	Model 1: 443	Model 1: 2	1
	Model 2: 782	Model 2: 4	
	Model 3: 329	Model 3: 2	
	Model 4: 249	Model 4: 4	
	Model 5: 389		
	Model 6: 242		
Nb of total module per GSP	2434	12	1
Nb of Circuit per Model	Model 1: 2	Model 1: 18	7
	Model 2: 2	Model 2: 9	
	Model 3: 3	Model 3: 12	
	Model 4: 3	Model 4: 7	
	Model 5: 3		
	Model 6: 6		
Total Nb of circuit	6803	124	7
Total Nb of transformer	2434	24	1
Capacity of transformer/model (MVA)	Model 1: 0,04	Model 1: 25*2	160
	Model 2: 0,063	Model 2: 16*2	
	Model 3: 0,1	Model 3: 16*2	
	Model 4: 0,16	Model 4: 25*2	
	Model 5: 0,25		
	Model 6: 0,63		

Example of line/cable information

Cross section (mm^2)	Over Head Line (OH)				
	R (Ohm/km)	X (Ohm/km)	Capacity (MVA)	Variable Capital Cost (€/MVA/km)	Fixed Capital Cost (€)
25					
35					
50					
70					
120					
240					

Annex 2 Results of the data collection for selected countries

A number of countries have been selected in order to run specific analyses on the basis of load and generation scenario forecasts provided by the partners, as well as typical distribution network configurations and characteristics. The data collection has been carried out through the template for the GDS model developed in this work package. In this section, some of the information provided, relevant to load and generation scenarios, are summarized for the selected countries.

Annex 2.1 Poland

A 2.1.1 *Load scenarios*

The total peak load for an average GSP (there are 103 GSPs in Poland) is estimated equal to 118 MW, with the voltage distribution breakdown and load increase given in Table A.1. Typical load profiles are provided in Figure A.1.

As a matter of nomenclature, the picture referring to residential load without electrical heating presents a *legenda* for the different characteristic days considered in the model, which also applies in the subsequent pictures with the following key:
Winter Weekday = WW = Series 1;
Winter Saturday = WSat = Series 2;
Winter Sunday = WSun = Series 3;
Intermediate (Spring/Autumn) Weekday = IW = Series 4;
Intermediate Saturday = ISat = Series 5;
Intermediate Sunday = ISun = Series 6;
Summer Weekday = SW = Series 7;
Summer Saturday = SSat = Series 8;
Summer Sunday = SSun = Series 9.

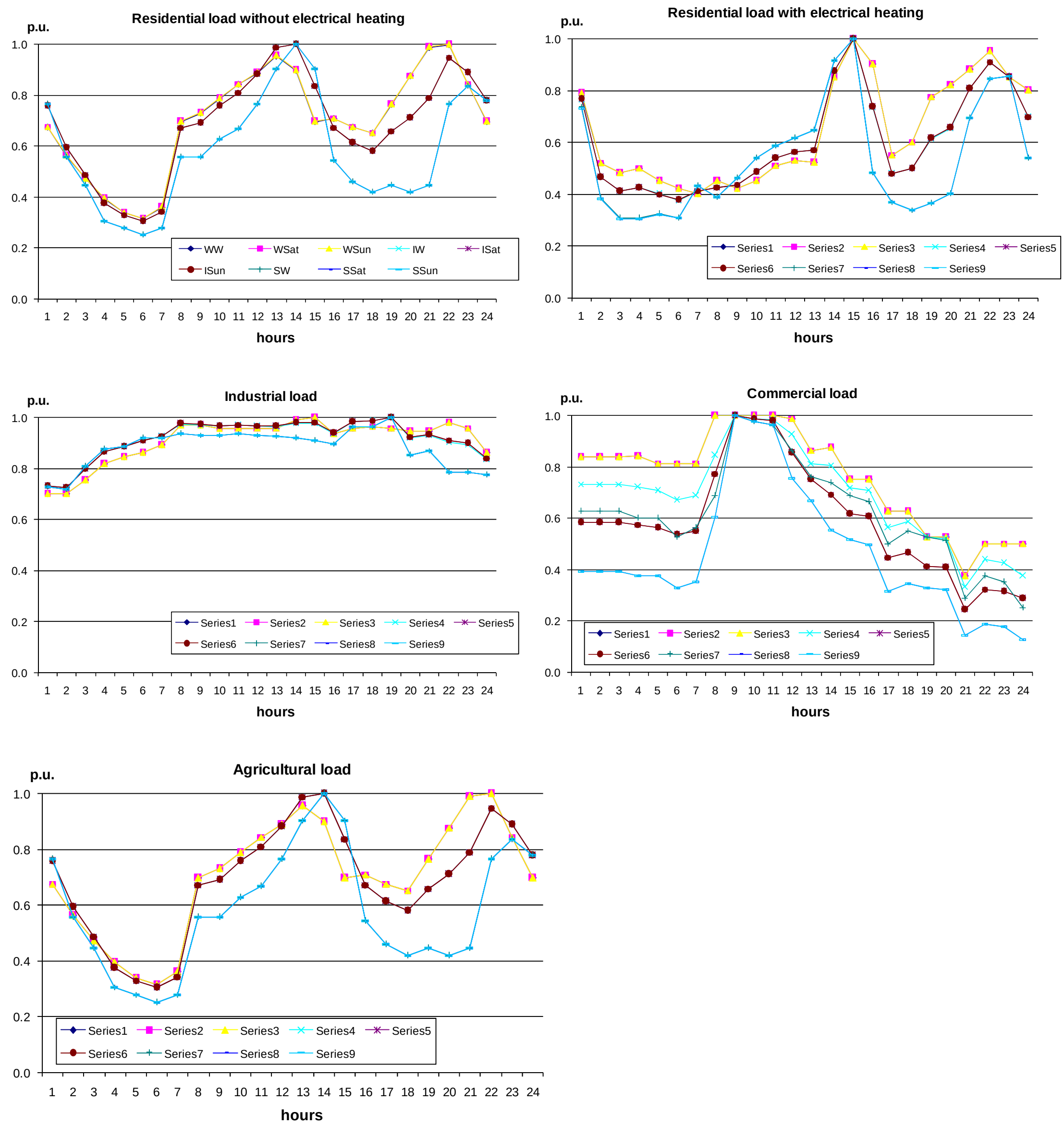


Figure A.1. Typical load profiles for different user typologies, Poland.

Table A.1. Typical load scenarios for Poland.

GSP Total Maximum Load (MW)	118
Percent of Max load connected at 0.4kV network	35
Percent of Max load connected at 15kV network	65
Percent of Max load connected at 110kV network	0
Estimated annual load increase %	5.15

A 2.1.2 *Generation scenarios*

The total DG installed capacity in Poland, with forecast up to 2020, is provided in Table A.2, while the penetration level per GSP is shown in Table A.3. In addition, Table A.4 shows a typical breakdown by voltage for the different DG typologies. Figure A.2shows typical generation profiles for the different technologies.

Table A.2. Total DG installed capacity (MW) scenarios for Poland.

Type	today	2010	2015	2020
Onshore Wind	300	400	5000	13600
Micro CHP	40	200	1500	2000
PV	0	0	50	125
Biomass	30	100	2000	5000
HydroGen	2500	2700	3000	3000
Landfill Gas	105.6	264	396	528

Table A.3. DG penetration level scenarios per GSP (MW) for Poland.

Type	today	2010	2015	2020
Onshore Wind	300	400	1500	1100
Micro CHP	40	90	200	150
PV	0	0	10	15
Biomass	30	100	300	500
HydroGen	0	10	30	50
Landfill Gas	10	12	40	50

Table A.4. Typical DG penetration breakdown by voltage level for Poland.

For each penetration level		Percent of installation among different voltage level (%)		
Type	**Max Capacity/GSP(MW)**	**0.4kV**	**15kV**	**110kV**
Onshore Wind	0.6	15	85	0
Micro CHP	20	60	40	0
PV	0	100	0	0
Biomass	30	20	50	30
HydroGen	0.516	26	74	0
Landfill Gas	0.4	0	100	0

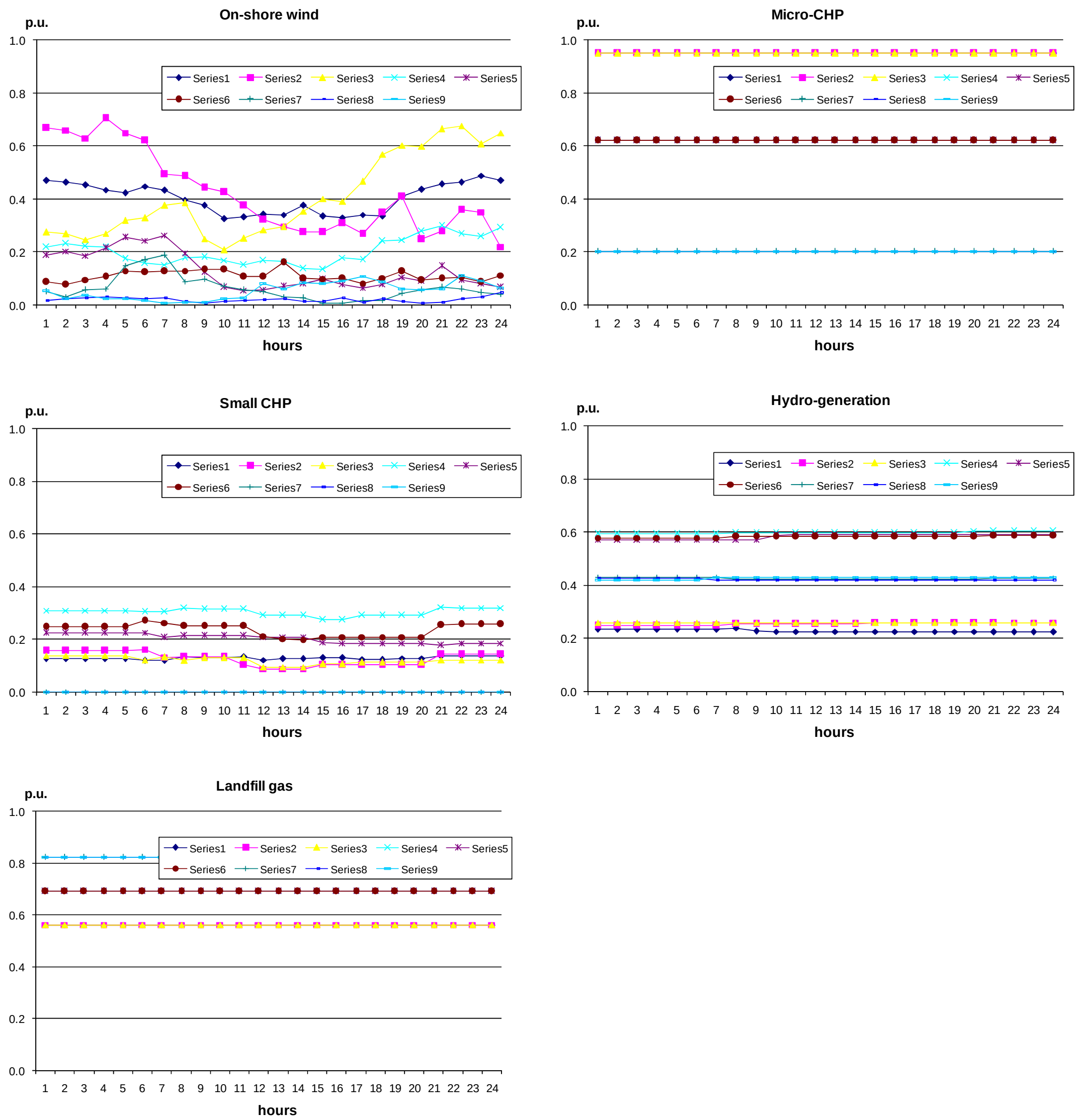


Figure A.2. Typical generation profiles for different technologies, Poland.

Annex 2.2Macedonia

A 2.2.1 *Load scenarios*

The total peak load for an average GSP (there are 3 GSPs in Macedonia) is estimated equal to 660 MW, with the voltage distribution breakdown given in Table A.5. Typical load profiles are provided in Figure A.3.

Table A.5. Typical load scenarios for Macedonia.

Total Maximum Load (MW) IN GSP	600
Percent of Max load connected at 0.4kV network	57
Percent of Max load connected at 10kV network	10
Percent of Max load connected at 35kV network	1
Percent of Max load connected at 110kV network	32

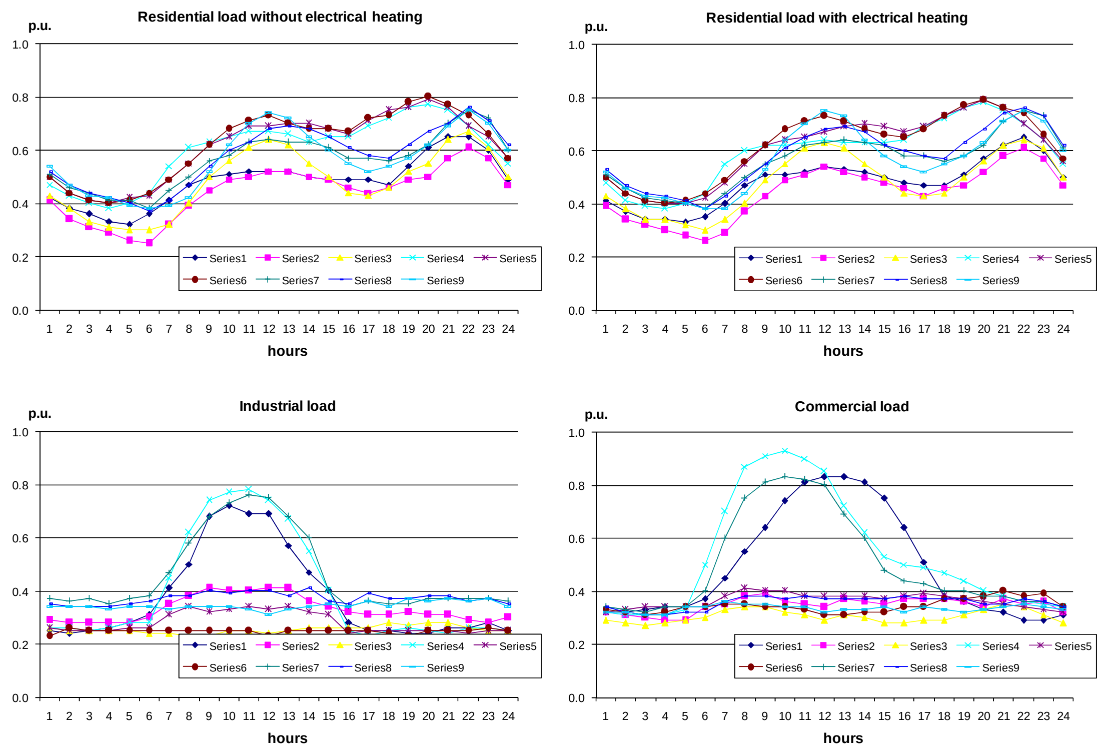


Figure A.3. Typical load profiles for different user typologies, Macedonia.

A 2.2.2 *Generation scenarios*

The total DG installed capacity in Macedonia, with forecast up to 2030, is provided in Table A.6, while the penetration level per GSP is shown in Table A.7. In addition, Table A.8 shows a typical breakdown by voltage for the different DG typologies. In particular, one large CHP is envisaged to be installed by 2015, and to be connected at HV, while hydro plants are connected at a MV level (35 kV). Figure A.4 shows typical hydro-generation profiles.

Table A.6. Total DG installed capacity (GW) scenarios for Macedonia.

Type	today	2015	2020	2030
Large CHP		0.2[1]	0.2	0.2
HydroGen	0.040	0.065	0.090	0.115

[1] There is only one large CHP plant expected to enter in operation in 2015.

Table A.7. DG penetration level scenarios per GSP (MW) for Macedonia.

Type	today	2015	2020	2030
Large CHP		200	200	200
HydroGen	14	21	31	37

Table A.8. Typical DG penetration breakdown by voltage level for Macedonia.

For each penetration level		Percent of installation among different voltage levels (%)			
today					
Type	**Max Capacity/GSP(MW)**	**0.4kV**	**10kV**	**35kV**	**110kV**
Large CHP					
HydroGen	14			100	
2015					
Type	**Max Capacity/GSP(MW)**	**0.4kV**	**10kV**	**35kV**	**110kV**
Large CHP	200				100
HydroGen	21			100	
2020					
Type	**Max Capacity/GSP(MW)**	**0.4kV**	**10kV**	**35kV**	**110kV**
Large CHP	200				100
HydroGen	31			100	
2030					
Type	**Max Capacity/GSP(MW)**	**0.4kV**	**10kV**	**35kV**	**110kV**
Large CHP	200				100
HydroGen	37			100	

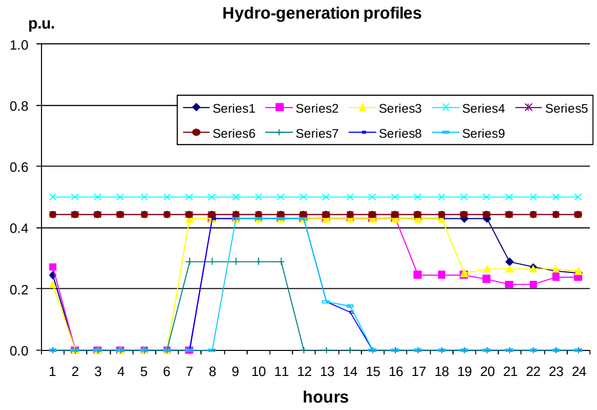


Figure A.4. Typical hydro-generation profiles, Macedonia.

Annex 2.3Netherlands

A 2.3.1 *Load scenarios*

The total peak load for an average GSP (there are 300 GSPs in Poland) is estimated equal to 60 MW, with the voltage distribution breakdown and load increase given in Table A.9. Typical load profiles are provided in Figure A.5.

Table A.9. Typical load scenarios for Netherlands.

GSP Total Maximum Load (MW)	66
Percent of Max load connected at 0.4kV network	40
Percent of Max load connected at 11kV network	30
Percent of Max load connected at 33kV network	20
Percent of Max load connected at 132kV network	10
Estimated annual load growth %	2

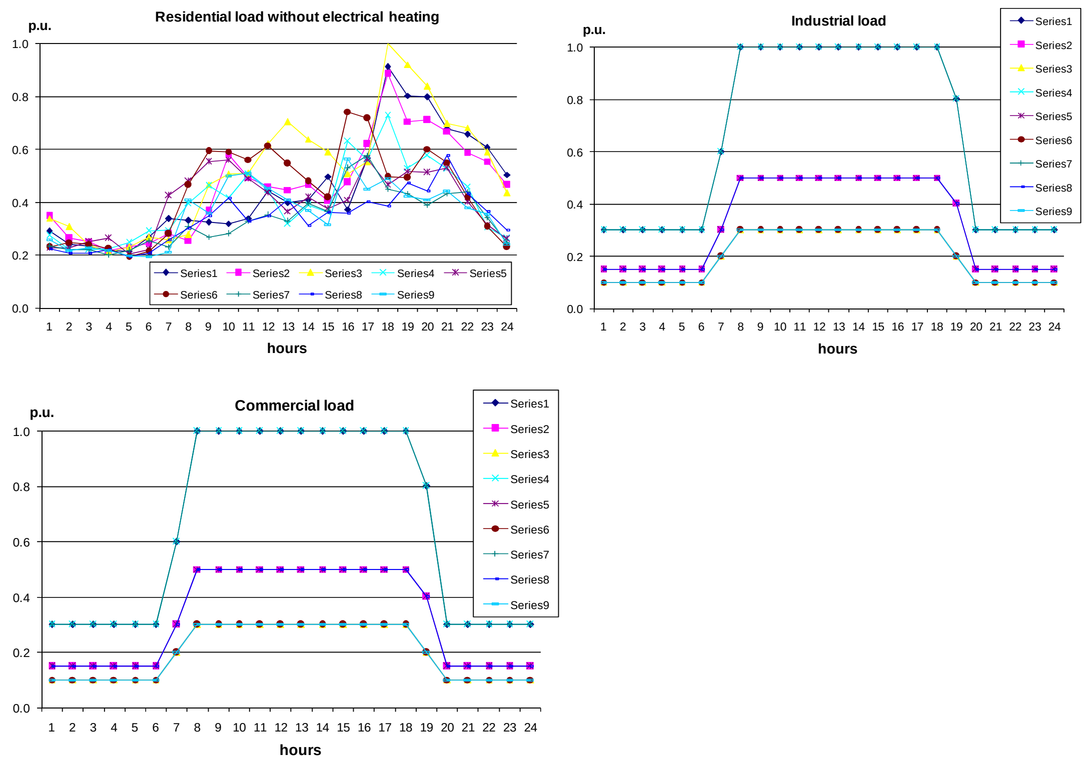


Figure A.5. Typical load profiles for different user typologies, Netherlands.

A 2.3.2 *Generation scenarios*

Table A.10 shows a typical breakdown by voltage level for the different DG typologies to be installed in the Netherlands, while Figure A.6 shows typical generation profiles for the different technologies.

Table A.10. Typical DG penetration breakdown by voltage level for Netherlands.

For each penetration level		Percent of installation among different voltage level (%)			
Type	Max Capacity/GSP(MW)	0.4kV	11kV	50 kV	150 kV
Offshore Wind	40	0	0	0	100
Onshore Wind	40	0	80	20	0
Micro CHP	40	100	0	0	0
Small CHP	40	50	50	0	0
Medium CHP	40	0	100	0	0
Large CHP	40	0	50	50	0
PV	40	100	0	0	0

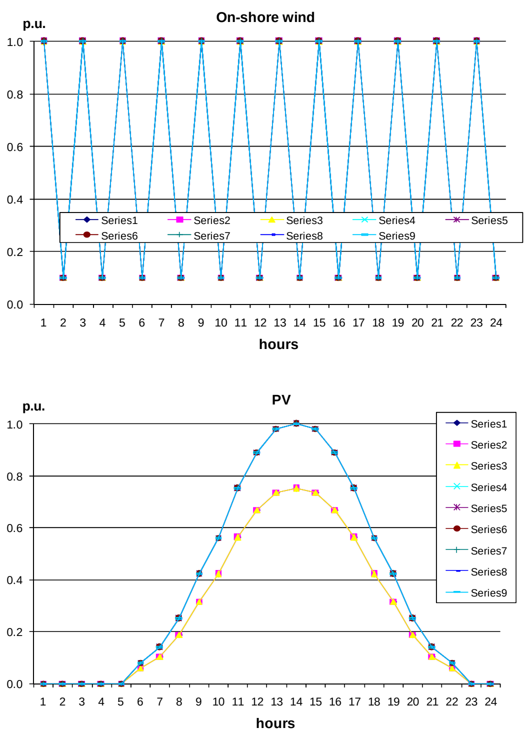


Figure A.6. Typical generation profiles for different technologies, Netherlands.

Annex 2.4Germany

A 2.4.1 *Load scenarios*

In Germany there are 270 GSPs, Rather than an average estimate, the total peak load and the relevant information have been provided for a specific network, with a peak load of 474 MW, and with breakdown by voltage level and annual load growth ration given in Table A.11. Typical load profiles are provided in Figure A.7.

Table A.11. Typical load scenarios for Germany.

Total Maximum Load (MW) in GSP	484
Max load at 0.4kV(%)	33
Max load at 11kV (%)	44
Max load at 132kV (%)	23
Estimated annual load increase %	0.68

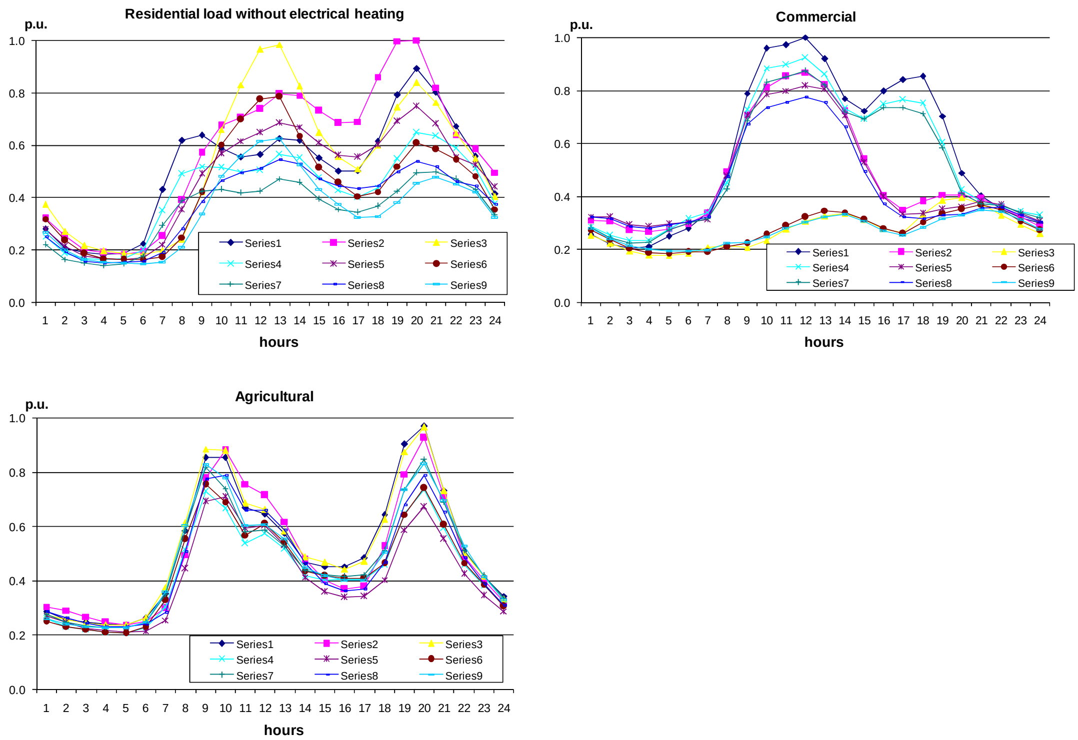


Figure A.7. Typical load profiles for different user typologies, Germany.

A 2.4.2 *Generation scenarios*

The total DG installed capacity in Germany, with forecast up to 2030, is provided in Table A.12, while the penetration level per GSP is shown in Table A.13. In addition, Table A.14 shows a typical breakdown by voltage for the different DG typologies. Figure A.8 shows typical generation profiles for the different technologies.

Table A.12. Total DG installed capacity (GW) scenarios for Germany.

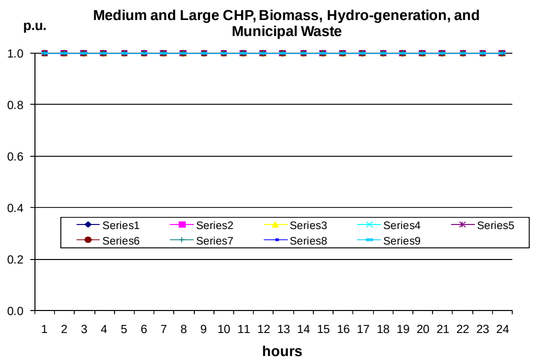
Type	today	2015	2020	2030
Offshore Wind	0.01	10	20	30
Onshore Wind	20.6	26	28	30
Micro CHP	1.6	4.1	5.3	7.8
Small CHP	2.7	5.2	6	6.5
Medium CHP	6	6.8	7.1	7.4
Large CHP	10	11.4	11.8	13.2
PV	2	7.5	10	13.7
Biomass	2.1	5.4	6.6	7.9
HydroGen	4.8	5	5.1	5.1
Landfill Gas	0.351	0.334	0.32	0.3
Industrial Waste	2	2.5	3	3

Table A.13. DG penetration level scenarios per GSP (MW) for Germany.

Type	today	2015	2020	2030
Offshore Wind	0	0	0	0
Onshore Wind	0	0	0	0
Micro CHP	0.05	15	40	70
Small CHP	1	3	10	15
Medium CHP	60	70	80	90
Large CHP	0	0	0	0
PV	2	8	15	20
Biomass	20	30	45	60
HydroGen	5	5	7.5	7.5
Landfill Gas	0	0	0	0
Industrial Waste	43	60	60	80

Table A.14. Typical DG penetration breakdown by voltage level for Germany.

For each penetration level		Percent of installation among different voltage levels (%)		
Type	Max Capacity/GSP(MW)	0.4kV	20kV	110kV
Offshore Wind	0	0	0	0
Onshore Wind	0	0	0	0
Micro CHP	70	90	10	0
Small CHP	15	0	100	0
Medium CHP	90	0	70	30
Large CHP	0	0	0	0
PV	20	60	40	0
Biomass	60	0	0	100
HydroGen	7.5	0	100	0
Landfill Gas	0	0	0	0
Industrial Waste	80	0	0	100



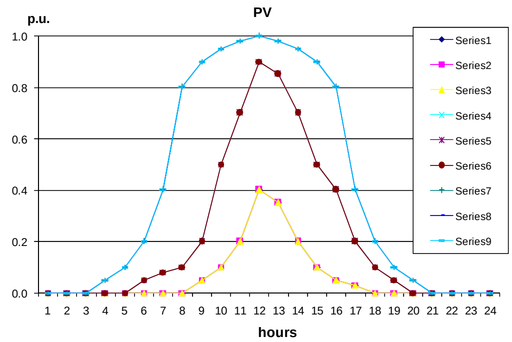


Figure A.8. Typical generation profiles for different technologies, Germany.

Annex 2.5 UK

A 2.5.1 *Load scenarios*

Figure A.9 shows typical load profiles for different user types in the UK.

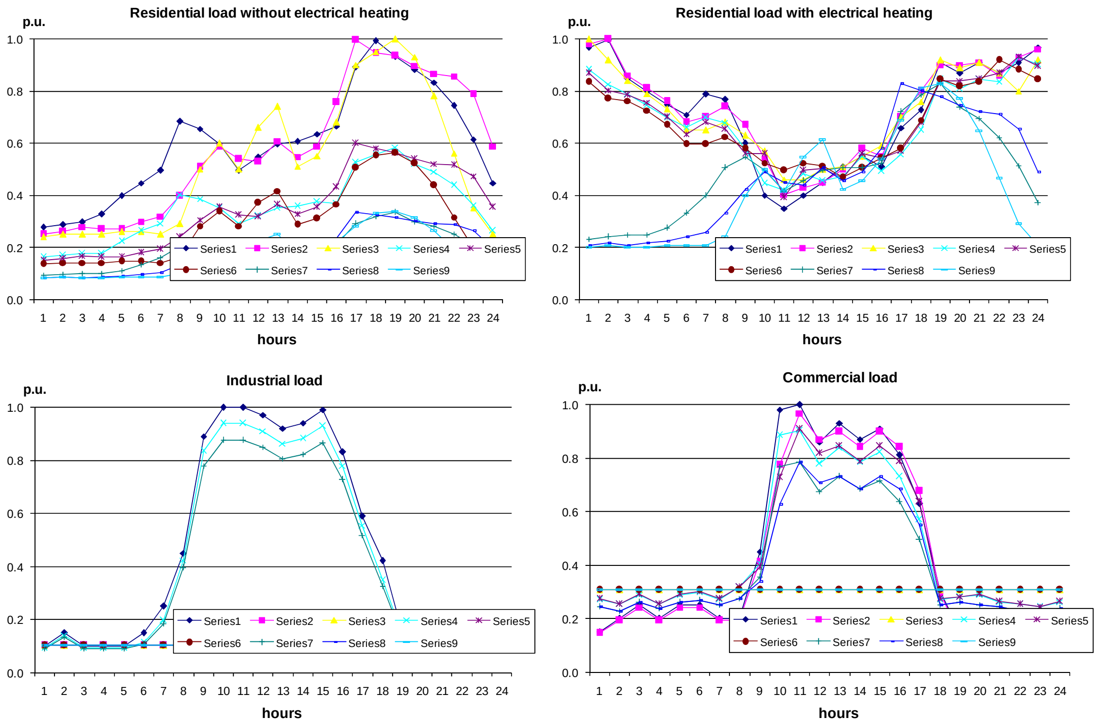


Figure A.9. Typical load profiles for different user typologies, UK.

A 2.5.2 *Generation scenarios*

Figure A.10 shows typical generation profiles for different micro-technologies used in the UK.

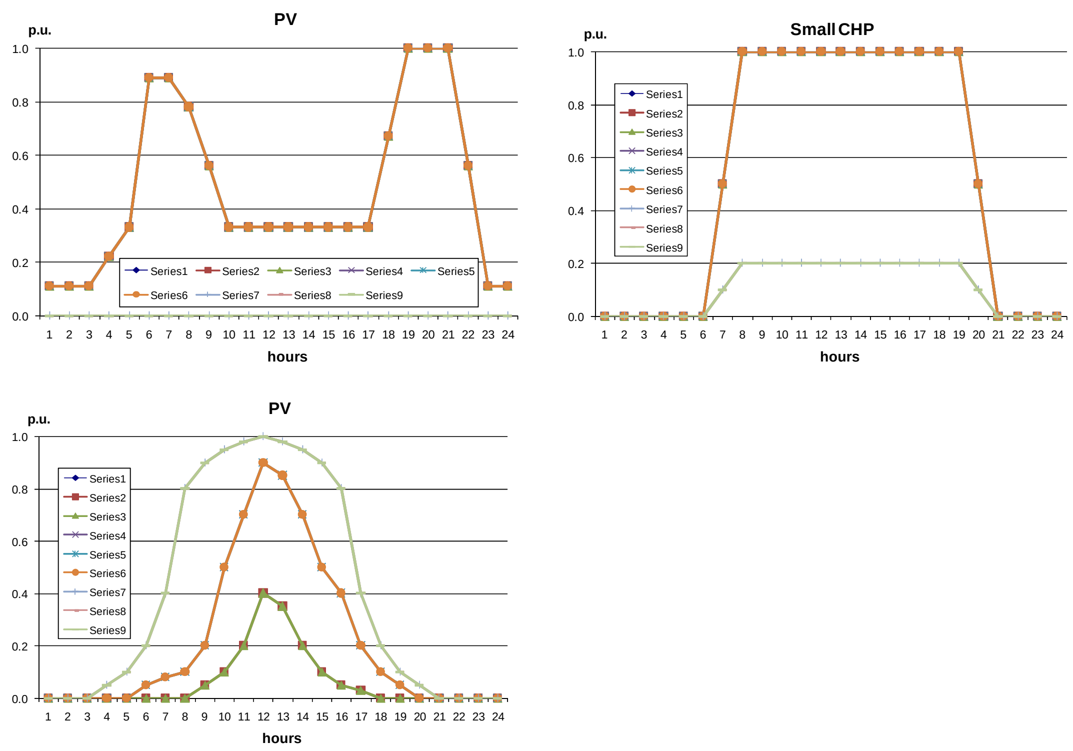


Figure A.10. Typical generation profiles for different DG systems, UK.