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Optimal planning of future distribution grids under consideration of Smart Grids and Smart Markets

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Final Report Smart Planning



Project Smart Planning
Optimal planning of future distribution grids under consideration of Smart Grids and Smart Markets













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I. Summary

Installation of substantial numbers of distributed generation (DG) units in the distribution network results in a paradigm shift of generation from the top to the bottom of the power systems. Furthermore, energy storage systems, active demand such as heat pumps and the electrification of the transportation will become main part of future distribution systems, causing new challenges and requirements while planning and operating distribution networks. The mentioned devices influence the power flows significantly, causing the need for grid upgrades. Currently, distribution system operators (DSOs) face these challenges in a passive manner by conventional network reinforcement measures (passive DSO) without considering the frequency and duration of critical network loadings and voltage violations.
New technologies and measures become available which provide new opportunities to face these challenges. The implementation of these new technologies and measures such as on load tap changer transformers (OLTC), battery energy storage systems (BESS) or active and reactive power curtailment of DG can be summarized under the label *Smart Grid*. Related to Smart Grids there are so called *Smart Market* activities, which create values by managing consumers' loads to provide market products or ancillary services. Collectively, the set of Smart Grids technologies and Smart Market activities can be named as smart options.
The regulation influences the planning of distribution networks, however as regulation differs in European countries and will be probably adjusted in the future no regulatory barriers for smart options are assumed in our study. Therefore the results of the project can be used to help policy makers to adjust regulation to new energy systems challenges.
As a consequence of the changing supply task and the emerging smart grid technologies and market options, the electrical distribution network planning process becomes more complex due to growing numbers of possible planning options and their interdependencies. DSOs have to adapt their planning process by considering smart grid technologies and smart market options to achieve better planning strategies, becoming an active DSO.

The smart planning project analyses how new distribution network planning guidelines should look like and how to find the most suitable expansion alternative between conventional network upgrade and smart options. The main issues addressed by the smart planning project are:

- How to evaluate smart options and incorporate these in common European innovative planning guidelines
- How renewable energies and flexible loads will affect distribution network planning activities as well as their grid impacts.
- Which expansion options are most economic under given circumstances/network topologies

To perform a comprehensive study and ensure that the point of view of all relevant stakeholders are reflected, the project focuses on various aspects of the 7th Framework Program of the EU and other related programs of European countries. This report is the result of the work performed by this consortium over the past three years. The report is structured into four thematic blocks including overall seven chapters as depicted in Figure A below.

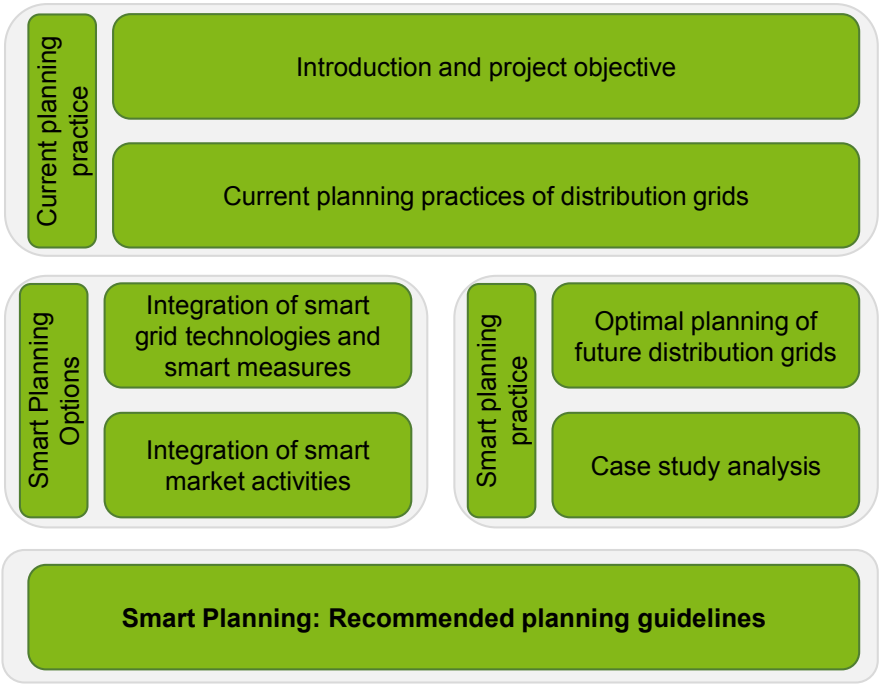


Figure A: Report structure

Different models and planning tools have been set up to perform the analysis and guide the research to the final result. As an example, models to present the behaviour of DG units, loads and different smart grid technologies were developed. Moreover, an agent based model was developed and used to represent the behaviour and interaction of Distributed Energy resources (DER) under different market conditions and scenarios. In addition, an optimization model was formulated and implemented to derive the optimal planning strategy for several cases considering different planning options. The Smart planning project considers within its final results the experience and findings of other research, pilot projects as well as case studies from the literature. Based on these, general planning recommendation are developed towards the most suitable planning of distribution networks. These can be incorporated into common European guidelines. Resulting guidelines may help the planner to consider smart options during the distribution network planning process. The following recommendations are general hints in order to find the most efficient network expansion options, but cannot replace a detailed planning by the DSOs as distribution network planning is highly case dependent:

General Recommendations

- The smart planning project has shown that conventional grid expansion will still be necessary in the future. However, by combining it with smart options at the right time, Distribution System Operators (DSOs) can reduce their costs.
- Information and Communications Technologies (ICT) will play an important role as one of the main factors enabling the flexibilities. In order to plan smart, DSOs would benefit from getting access to the building's management system. To achieve that, a proper interface and potentially a monitoring system are also necessary. However, the reliability and cost of ICT should be justified and reflected precisely in the planning stage.
- To capture the behaviour of the grid, the time variability of the generation and demand profiles has to be adopted in the planning calculations. Probabilistic and time series techniques should be used to capture the stochastic and volatile behaviour of loads and generation units. Hence, the result of the network calculations should presents the asset loading and nodal voltage stochastically.
- In smaller geographical regions, there is a high correlation between the feed-in of each individual type of intermittent DG unit. Therefore, especially for the wind turbine the time series of one generator can be considered relatively representative for other generators of the same type in the same region if implementation of measurement is costly. However, for PV-units pollution and clouds can lead to different local behaviours.

Smart Grid Technologies and Measures

- The costs for Line Voltage Regulators (LVR) and On-Load Tap Changers (OLTC) can be slightly lower in comparison to conventional grid reinforcement. However, the final decision of choosing these options depends on grid characteristics such as the arrangement of the feeders, voltage level, and load/feed-in distribution.
- Battery energy storage systems proved to be an expensive option, but a considerable investment cost reduction is expected for the next years
- Active power curtailment and reactive power support of DG units are in general preferable planning options.
- Active power curtailment is an efficient measure to solve both overloading problems as well as overvoltage issues. However, since it is frequently linked with operational costs, reactive power control is prioritized to cope with both under- and overvoltage's mainly in networks with high $\frac{R}{X}$ ratio.
- If the grid constraints are violated rarely, active power curtailment and reactive power support of DG units are likely the most economic options compare to the other planning options
- Dynamic active power curtailment of DG units is more efficient than static active power curtailment, but requires ICT infrastructure. Depending on the cost of ICT, static approaches might be more preferable.

- Reactive power support of DG units based on $Q(V)$ method is more efficient than $cos\,\varphi(P)$ method.
- Centralized coordinated reactive power support of DG units is more efficient than decentralized reactive power support, but requires ICT infrastructure. Depending on the cost of ICT, different distribution control approaches might be more preferable.

Customer Flexibility Potential

- The flexibility currently available in households mainly comes from white goods and is limited with respect to the amount of power that on average can be shifted. The flexibility potential is however expected to grow substantially with an increasing penetration of electric vehicles and heat pumps which are shown to have a large potential for load shifting in real life setups.
- The use of smart appliances, which can (semi-)automatically respond to time-varying prices, provides more (and more reliable) flexibility than manual response.

Smart Market Impact

- Implementation of a local smart market, with the goal of balancing of balancing locally supply and demand, can substantially reduce the peak loading in the grid and thereby defer the need for grid investments.
- In distribution networks with a large amount of generation, implementation of a local market will be more attractive than in load dominated networks, as the availability of local generation leads to a more effective operation of the market. An effective market results in lower average prices and a larger reduction in peak loading.
- Implementing market strategies where the DSO can additionally deploy flexibility for grid services improves the operation of the networks, by resolving congestion. But to ensure grid robustness, a fail-safe mechanism should also be in place, e.g. in the form of direct grid control, as the market may not always be able to clear itself within the grid constraints.
- There are still many uncertainties and restrictions, hindering the integration of a local smart market as a reliable long term planning alternative. Most notably, the willingness of customers to participate in such markets, the reliability and security of the necessary ICT infrastructure, and the regulatory changes required to operate such a market and allow DSOs to participate to some extent.

Combined Smart Options

- In LV grids with short cable distances, the conventional grid reinforcement combined with active power curtailment by DGs, as well as reactive power control might comprise the most cost-efficient combination among the planning options. Battery energy storage systems will complement PV units and will become attractive as their cost decrease, or in case the other available active measures become expensive due to regulation.

- In MV grids, the distances among the different nodes are larger than in the LV case, and thus, the direct control measures seem to be the most economic planning alternatives. Wind power, not following specific typical daily patterns, does not favour the installation of battery energy storage systems, whose capacity should be very large. The use of transformers equipped with OLTCs can solve in an economical way most of the overvoltage issues arising from high distributed generator penetration.

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III. List of abbreviations

APC	active power curtailment
BESS	battery energy storage system
BFS	backward forward sweep
CAPEX	capital expenditure
CL	controllable load
DER	distributed energy resource
DG-units	distributed generation units
DSM	demand side management
DSO	distribution system operator
EAC	equivalent Annual Cost
EV	electric vehicle
HP	heat pumps
ICT	information and communications technology
LV	low voltage
LVR	Line voltage regulator
MAS	multi-agent system
MILP	mixed integer linear program
MV	medium voltage
OLTC	on load tap changer
OPEX	operational expenditure
OPF	optimal power flow
PCC	point of common coupling
PV	Photovoltaic
RPC	reactive power control

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1 Introduction

1.1 Scientific and technical objectives

Distribution networks for electrical energy are facing numerous new requirements and challenges caused by the increased amount of installations of distributed generation (DG) as well as new loads (electric vehicles (EV), heat pumps (HP)) at low and medium voltage levels. Besides the general fact that these devices influence (and DGs even reverse) the power flows significantly causing the need for grid upgrades in the distribution network, another aspect is that fluctuating energy sources make the power flows highly volatile. Currently, distribution system operators (DSO) face these challenges in a passive manner by conventional network reinforcement measures (passive DSO) without consideration of the frequency and duration of critical network loadings and voltage violations due to highly volatile power flows.
At the same time, new technologies and measures become available which provide new opportunities to face these challenges. The implementation of these new technologies and measures such as on load tap changer transformers (OLTC), battery energy storage systems (BESS) or active and reactive power curtailment of DG can be summarized under the label *Smart Grid*. Related to Smart Grids there are so called *Smart Market* activities, which create values by managing consumers' loads to provide market products or ancillary services. Collectively, the set of Smart Grids technologies and Smart Market activities can be named as smart options.
In theory, the Smart Market could cause grid extensions, but could be able to be used for grid relief as well. This mutual impact could lead to an optimum of value creation on the marked side, by minimizing the need for network extension.
As a consequence of the changing supply task and the emerging smart options, the electrical distribution network planning process gets more complex due to growing numbers of possible planning options (network expansion options) and their interdependencies. DSOs have to adapt their planning process by considering smart options to achieve better planning strategies, becoming an active DSO.

The smart planning project analyses how new distribution network planning guidelines should look like and how to find the most suitable expansion alternative between conventional network upgrade and smart options. The main issues addressed by the smart planning project are:

- How to evaluate smart options and incorporate these in common European innovative planning guidelines
- How renewable energies and flexible loads will affect distribution network planning activities as well as their grid impacts
- Which expansion options are most economic under given circumstances/network topologies

To answer these questions, today's planning guidelines are analysed and models of real networks in selected European countries are created/collected. These models are modified to include new technological options and fed by load and generation time series in appropriate resolution. These time series reflect the particular behaviour of prosumers and consumers. Depending on the analysis either time series for representative days or for the full year are chosen.
However, as distribution networks are very heterogeneous, it is practically infeasible to create detailed individual models of all kinds of distribution network configurations. To consider different market situations and network loadings, key indicators are derived based on the analysed grid models to guarantee the generality of the presented planning methodology.
Overall the term *planning guidelines* already indicates a certain degree of generalisation which is justifiably applied in this project as well. In this way, a common understanding of bottlenecks in current planning practice, as well as possible solutions to overcome these bottlenecks are derived. Consequently, the given recommendations are applicable for all DSOs and can be integrated and adjusted into/to DSOs individual planning process.

1.2 Description of the project consortium

Smart Planning is an international research project with partners from three different European countries. The partners of each country form a team, which consists of one research organization and one system operator/ industry member, as illustrated in Table 1-1.

Table 1-1: Project consortium of Smart Planning

Team Germany	tu	TU Dortmund
	ABB	ABB AG
Team Netherlands	TU/e	TU Eindhoven
		Enexis B.V.
Team Switzerland	ETH	ETH Zürich
	ewz	Ewz

1.3 Current state of science and technology

Nowadays, during the planning during the planning of distribution networks, considered supply scenarios, considered supply scenarios are usually very conservative. Assumptions for combinations of maximum renewable feed-in with minimum loads (and vice versa) are set on extreme values. For example, in Germany, typical scenarios for the design of networks on the low voltage level are 85% of Photovoltaic (PV) feed-in with only 10% load at the same time. Or on the medium voltage level the design is typically based on 85% PV in combination with 100% wind and 20% load [1]. Even if local weather situations never show 85% penetration of PV together with 100% wind, these conservative assumptions are considered [2].
In many European countries the (N-1) criterion is used on the medium voltage level to guarantee a high quality of supply. For distributed generation (DG) typically an (N-0) criterion is sufficient. If the network design for grids with a high share of DG is based on the (N-0) criterion, line tripping can cause overloading/overvoltage in situations with large generation. In such situations, DG units could be curtailed immediately when an (N-1) case occurs by means of control technologies and information and communications technology (ICT). As a consequence, fewer investments will be necessary and generation curtailment will only happen in contingency situations combined with large amount of generation [1]. This is beyond the current state of the art in network planning for most European countries. For instance, low voltage networks in Germany are designed for a loading up to 100% during normal operation (N-0 criterion).
To determine the needed amount of installed capacity of the distribution system nowadays, the diversity factor is used to estimate the maximum load, which assumes that not all loads will use the entire installed capacity simultaneously [3]. However, the current practice of calculating the diversity factor does neither consider the probability distributions for this maximum load, or generation nor the fact that intelligent measures could smooth the loading profile. For future network planning, the consideration of these probabilities will be of high importance, especially in combination with active and reactive power curtailment, demand side management or battery storage systems which all aim at influencing the network loading, by managing the actual load and feed-in of the grid. However, in most European countries, this kind of curtailment is currently only permitted as a temporary measure to avoid network expansion – even if it could be in mid- or long-term economic efficient in some cases.
The network integration of new loads (and particularly their operational behaviour), such as electric vehicles, will also have a significant influence on the network requirements and is so far not considered for planning guidelines or only in a very rudimentary. These additional loads lead to the need of high investments into the distribution networks, especially considering today's planning praxis [4]. The use of smart planning approaches could reduce these investments.
Furthermore, Smart Market activities have also an impact on the loading of the distribution system [5]. In general, Smart Market activities can either be driven by

the network operator, or by the market, and depending on the situation it can either lead to an increase or a decrease of line loadings. However, the impact of Smart Market activities on the grid condition is not included in the current grid planning guidelines.
There are several smart grid technologies and measures which are currently being researched. In the smart planning project the following technologies and measures are considered and investigated further:

- On load tap changer transformers
- Line voltage regulators
- Battery storage systems
- Active and reactive power control by DG
- Demand side management

Such options can help DSOs to optimize the utilization of the existing grid and to reduce the required amount of grid reinforcements. However, such technologies and measures are not considered by the majority of DSOs in their current planning guidelines [6].
In summary, current planning guidelines do not consider the probability of specific grid conditions due to the fluctuating generation, and therefore Smart Market activities and new smart grid technologies and measures are not reflected extensively in the planning guidelines. This leads to a conservative network planning with a large amount of redundancies. A detailed summary for DSOs current planning practice follows in chapter 2.

1.4 Report structure

The report is structured into four thematic blocks including overall seven chapters as depicted in Figure 1-1. In **chapter one**, the scientific and technical objective of Smart Planning is illustrated and a short overview of the project consortium as well as the current state of science and technology is given. In **chapter two**, the current practice of electrical distribution network planning is outlined and bottlenecks of current planning practice regarding the changing supply task are analysed. Chapter one and two build the first thematic block, i.e. the current state of art in distribution network planning.
The second thematic block describes smart grid options and consists of chapters three and four. In **chapter three,** different smart grid technologies and distribution network planning measures are analysed and evaluated in terms of economic and technical aspects. Based on the mentioned evaluation, functionalities of preselected smart grid technologies and measures are assessed in a test distribution network planning case by considering different renewable energy integration levels. **Chapter four** finalizes the second block with the consideration of smart market activities in electrical distribution planning. Thereby, it focuses on the potential im-

pact of flexibilities from DSM including new loads. **Chapter five** deals with the optimal planning of future distribution networks. In this chapter, the previously presented options are considered as competing options against each other and against conventional grid reinforcement measures. Therefore, an optimization model is formulated. Additional investigations that were conducted as part of the smart planning project will also be presented in the same chapter.

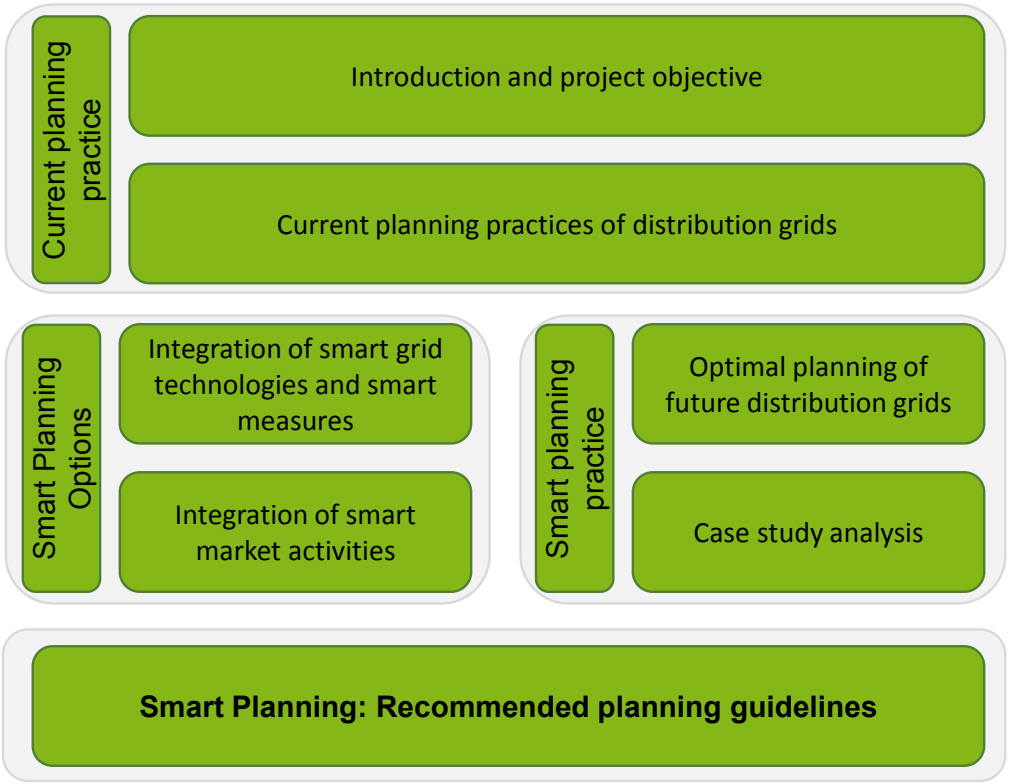


Figure 1-1: Report structure

In **chapter six,** the optimization model is used to identify the optimal combinations of network expansion alternatives for different typical distribution grids. In this context, a sensitivity analysis regarding capital and operational expenditures is performed. These two chapters build the third thematic block, i.e. the smart planning practice. The report closes with **chapter seven,** being the last thematic block and project outcome – planning guidelines. Here, a recommendation of future electrical distribution network planning guidelines, respectively the adjustment of the current planning practice based on the previous analysis is given.

1.5 List of publications in the context of smart planning

Paper and Conferences

C. Wagner, B. Nasiri, U. Häger, C. Rehtanz: **Smart Planning – future distribution grid planning under consideration of smart grids and smart markets**, VDE-ETG Fachtagung "Von Smart Grids zu Smart Markets 2015", Kassel, März 2015.

C. Wagner, C. Waniek, U. Häger: **Modeling of Household Electricity Load Profiles for Distribution Grid Planning and Operation**, IEEE POWERCON, Wollongong Australia, September 2016.

B. Nasiri, C. Wagner, A. Ahsan and U. Häger: **A New Perspective for Smart Distribution Grid Planning***, POWERCON, Wollongong, 2016.*

B. Nasiri, A. Ahsan, D. Mayorga Gonzalez, C. Wagner, U. Häger, C. Rehtanz **Integration of Smart Grid Technologies for Voltage Regulation in Low Voltage Distribution Grids**, IEEE ISGT Asia, Melbourne Australia, November 2016.

B. Nasiri, C. Wagner, U. Häger, C. Rehtanz: **Distribution Grid Planning Considering Smart Grid Technologies**, Cired 24th International Conference on Electricity Distribution, Glasgow, June 2017

S. Kippelt, C. Wagner, C. Rehtanz: **Consideration of New Electricity Applications in Distribution Grid Expansion Planning and the Role of Flexibility**, International ETG Congress 2017, Bonn, November 2017

S. Karagiannopoulos, P. Aristidou, A. Ulbig, S. Koch, G. Hug: **Optimal planning of distribution grids considering active power curtailment and reactive power control**, IEEE PES General Meeting, Boston, USA, 2016.

S. Karagiannopoulos, P. Aristidou, G. Hug: **Hybrid approach for planning and operating active distribution grids**, IET Special Issue: Distributed & autonomous dispatch and control for active distribution networks/microgrids potential scheme to realize plug & play of DER, vol. 11, no. 3, pp. 685–695, 2017.

S. Karagiannopoulos, P. Aristidou, G. Hug: **Co-optimisation of Planning and Operation for Active Distribution Grids**, in PowerTech, Manchester, UK 2017.

S. Karagiannopoulos, L. Roald, P. Aristidou, G. Hug: **Operational Planning of Active Distribution Grids under Uncertainty,** in IREP, Espinho, Portugal, 2017.

U. Markovic, E. Kaffe, D. Mountouri, F. Kienzle, S. Karagiannopoulos, A. Ulbig: **The Future Role of a DSO in Distribution Networks with High Penetration of Flexible Prosumers,** Cired 23rd International Conference on Electricity Distribution, Helsinki, 2016

P. Fortenbacher, M. Zellner, G. Andersson; **Optimal Sizing and Placement of Distributed Storage in Low Voltage Networks**, 19th Power Systems Computation Conference 2016, Genoa, Italy, 2015.

M. Tavernier, S. Karagiannopoulos, P. Fortenbacher, E. Kaffe, G. Hug; **Cost-Reliability Optimization of Automation and Protection Configurations in Active Distribution Grids**, (submitted) 20th Power Systems Computation Conference 2018, Dublin, Italy, 2018.

R. Bernards, J. Morren and J.G. Slootweg; **A basis for Smart Planning: Requirements for Expansion Planning of Future Distribution Networks,** Proceedings of the 23rd International Conference on Electricity Distribution (CIRED2015), 15-18 June, Lyon, France, 2015.

R. Bernards, J. Morren and J.G. Slootweg; **Incorporating the Smart Grid Concept in Network Planning Practices,** Proceedings of the 50th IEEE Universities' Power Engineering Conference, 1-4 Sept., Stoke-on-Trent, United Kingdom, 2015.

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2 Current planning practices of distribution networks

Currently, DSOs are changing their passive distribution networks towards a smart distribution network in order to efficiently improve their systems in a sustainable manner. This paradigm shift towards smart distribution networks requires re-engineering of the planning process marked as 'smart planning' [7]. Doing so, current planning methods for distribution networks are investigated to find the bottlenecks which resist the transition towards smart planning approaches. Different methods [8] have been used in the investigation such as

Desk research: an extensive literature review has been performed regarding the planning methods in distribution networks. The knowledge attained at this stage is used to develop survey-questionnaires.

Survey-questionnaires: the questionnaire has been sent to the different DSOs operated in the countries of the respective project consortium. The questions in the survey designed to focus on two aspects:

- The current planning methods in each respective DSO
- The expected changes in the future which eventually influence DSOs' planning

Expert talk: round table discussion to support the knowledge attained in the previous section**.**

Planning is defined as theoretical anticipation of instruments and steps, considering their sequence, which are required to achieve targets in the most efficient manner. When it comes to electrical networks, planning is considered as an optimization task with the target to minimize costs by taking into account the technical boundaries. [9] Figure 2-1 shows the identified generic process of conventional electrical distribution networks planning.

In the investigation, in order to maintain the consistency and comprehensiveness of the analysis of the current distribution network planning practices, all the typical planning steps presented below are considered. In general, the time horizon for the target planning of MV networks is 5 to 25 years, in LV networks the time horizon is shorter. However, in both voltage levels it highly depends on DSO's strategy and the planning has to be updated frequently according to the conditions.

The existing planning practice relies heavily on deterministic peak planning approaches, taking into account worst-case scenarios (e.g. 85% of Photovoltaic i feed-in with only 10% load in LV networks) without the consideration of load profiles. Accounting for typical load profiles is a key factor in future distribution network planning, due to the highly volatile and time dependent power flow, caused by a high share of fluctuating renewable resources (PV and wind) and controllable

loads. The time, the duration and the probability of occurrence of specific grid conditions, e.g. congestions, highly influence the evaluation of different planning alternatives [7]. For example, it may influence the consideration of smart technologies and market activities (e.g. curtailment of DGs, DSM, OLTC transformers, storages, etc.). Thereby, time series are either used for the actual load flow calculation, or analysed previously to derive matched scenarios for the planning in order to map the probability of occurrence of specific grid conditions.

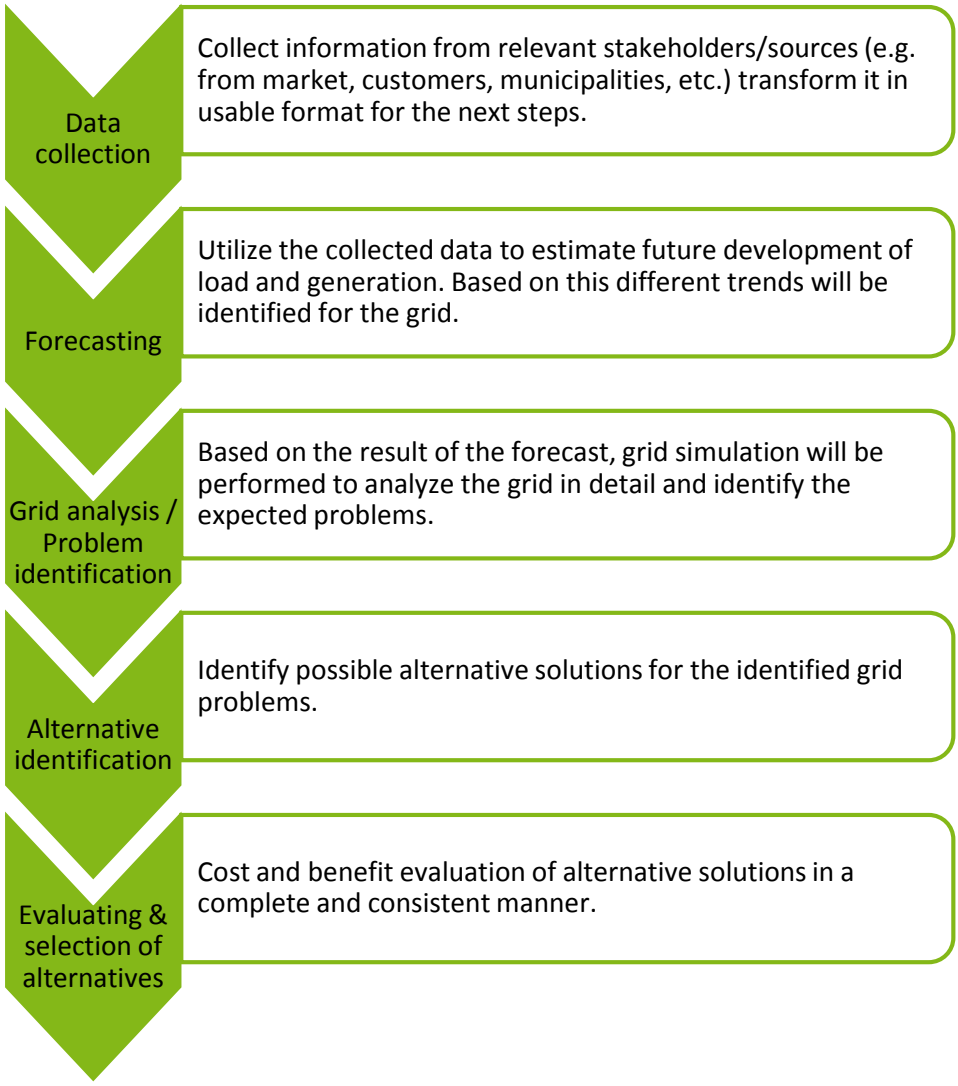


Figure 2-1: Typical electricity distribution network planning steps [8]

Currently, network reinforcement, i.e. installations of additional cable/line and transformer replacement, is the main option for the DSOs to tackle the problems in the network. Smart grid technologies, smart market options and smart measures are not fully considered as an alternative solution in the planning of the distribution networks as several uncertainties surrounding these alternatives [10]. Cost and benefits are often insufficiently clear, and furthermore, a clear regulation, which

may enable several new options, is still lacking. For instance, currently the curtailment of DGs is no viable option for the responded DSOs in most European countries, due to the regulation. Last but not least, there is a lack of comprehensive planning guidelines for distribution networks which should consider the aspects of smart grid technologies in combination with smart market activities and smart measures in the planning process

.

3 Integration of smart grid technologies and smart measures

3.1 Qualitative evaluation

Smart grid technologies and smart measures offer the possibility of reducing network expansion investment costs when considering the integration of DG units. Therefore, technologies and measures like energy storage and flexible loads could be used as smart options when the planning task is performed. In this regard, novel smart options for the distribution network planning are analysed and compared in terms of different qualitative aspects, as shown in Table 3-1. The used rating scale for this analysis is presented in Table 3-2.

A perfect communication infrastructure is considered for the evaluated alternatives, assuming that an adequate reliability and security communication level is available. Moreover, required information and communications technologies (ICTs) add extra complexity to the operation and planning of power systems, resulting, among others, in additional investments costs, that are not taken into account in this evaluation.

Furthermore, the performed analysis shows extraordinarily positive ratings in all evaluation criteria for *on-load tap changer (OLTC)*, *line voltage regulator (LVR)*, and *storage – supporting grid operation*. It should be noted that mainly on the MV level, it is restrictive to operate battery storage in a cost-efficient manner when compared to conventional grid extension alternatives. Nevertheless, in the near future a combination of conventional grid extension with storage could be cost-efficient due to the increasing needs of storage capacity [11].

The ‘transferability into a generic long term stable planning’ and ‘effectiveness of increasing the capability for the integration of additional distributed energy resources’ were the decisive evaluation criteria, and for this reason, in order to estimate the highest possible DER injection when considering different smart planning options, the following technologies were selected for further consideration in a MV network test system (chapter 3.2):

- OLTC
- LVR
- Storage – supporting grid operation

ICTs development plays a fundamental role in future distribution grids, mainly on the implementation of the *active power feed-in management*, that has demonstrated to be a beneficial planning measure compared to the conventional grid reinforcement [11]. For that reason, load management and feed-in management are analysed in detail in further chapters.

Table 3-1: Qualitative evaluation of smart planning options

Smart options	Wide area control - primary substation transformer	On-load tap changer (OLTC)	Line voltage regulator (LVR)	Storage - supporting grid operation	Feed-in management - active power	Feed-in management - reactive power	Load management – supporting grid operation	Automatic optimization of grid topology	**Evaluation criterion**
+	+++	++	++	++	++	+	o		Effectiveness of keeping the voltage limits
o	o	o	++	+++	--	+	o		Effectiveness of keeping the loading limits
+	++	++	++	++	+	o	o		Effectiveness of increasing the capability for the integration of additional distributed energy resources
+	+	+	+	+	+	-	-		Reduction of investment costs compared to conventional grid extension [1)]
-	++	++	++	+	+	o	-		Transferability into generic, long-term stable planning guidelines

[1)] only values **+** / **o** / **-** are used and show a trend (positive effect/ no effect / negative effect)

Table 3-2: Rating scale used for the qualitative evaluation

Designation	Indication
+++ / ++ / +	Improvement: Smart option has a very positive / positive / slightly positive effect with respect to the considered criterion
o	No change: Smart option has no effect with respect to the considered criterion
--- / -- / -	Worsening: Smart option has a very negative / negative / slightly negative effect with respect to the considered criterion

3.2 Consideration of new Smart Grid technologies

3.2.1 Cost curves of additional RES feed-ins achieved by considering Smart Grid technologies

In order to describe the behaviour of selected smart grid technologies (OLTC, LVR, and battery storage) an appropriate distribution network planning tool is required. Because of this, selected smart grid technologies were modelled, validated, and released in NEPLAN® version 5.5.7 with the aim to simulate the power system behaviour and to verify network loading and voltage levels.
A typical German rural MV grid (test system) was modelled and thus allowing to calculate the cost per additional MW injected by DERs when considering different planning smart options. The considered MV grid involves a 110 kV/ 10 kV primary substation with four 10 kV feeders. Each 10 kV feeders was modelled with its respective 10 kV/ 0,4 kV secondary substations. For each considered smart grid technology, feed-in increments of DG-units were performed (upscaling effect) until network overloads occurred or voltage band limits were violated. Investment costs for OLTC and battery storage are obtained from [12] and [13] respectively. The considered LVRs are rated for a maximum power transfer of 8 MVA with 350000 € investment costs per unit. Moreover, investment costs of conventional network expansion (grid reinforcement) were also considered on basis of ABB network expansion planning project expertise and used as a baseline to assess the impact of smart grid technologies. The investment costs of each smart grid technology are plotted as a function of additional feed-ins, as can be seen in Figure 3-1.

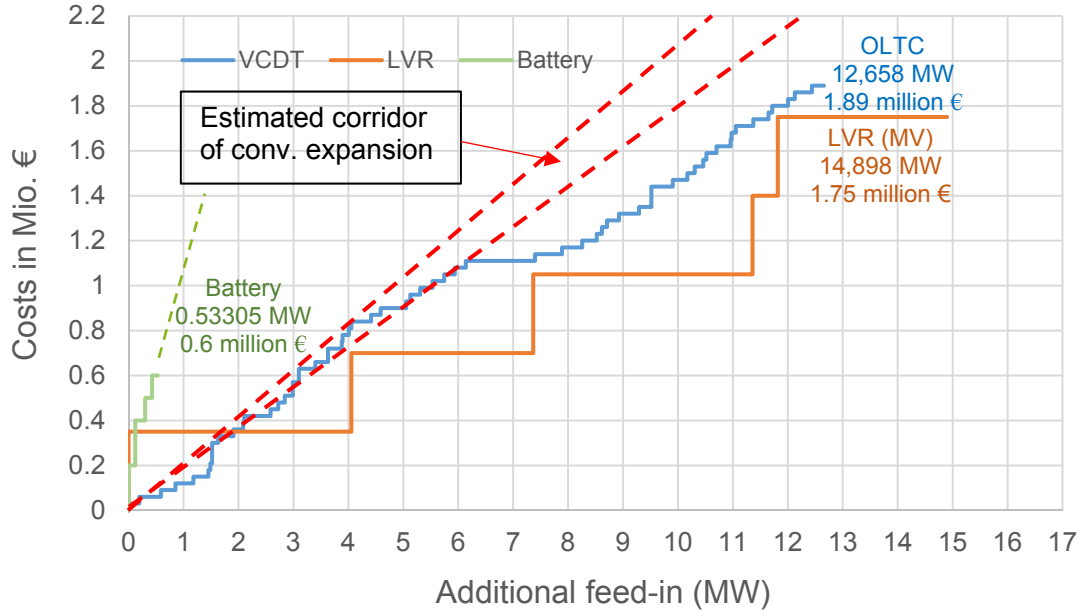


Figure 3-1: Expected costs per additional DER feed-ins for different planning smart options

Results show that LVR and OLTC present a slight cost benefit over conventional grid reinforcement for the grid under testing. Furthermore, battery storage proved to be an expensive option, but a considerable investment cost reduction is expected for the next 15 years as mentioned in [11]. However, these outcomes cannot be generalized because these are sensitive to investment cost assumptions, as well as network factors, such as the arrangement of the feeders, voltage level, load/feed-in distribution in LV grids, etc. Basis of the conducted analyses are four existing German rural MV-grids, where each branch is obtained from one of the mentioned grids.

3.2.2 Summary and Recommendation

The effectiveness of OLTC, LVR, and battery storage, as planning options was assessed. Mentioned smart grid technologies were modelled and implemented in a MV network test system in order to increase feed-ins of DERs. OLTC and LVR seem to be an adequate alternative to conventional grid reinforcement. Nevertheless, results are highly sensitive to assumed investment cost, as well as grid-topology and load/feed–in scenarios. In this respect, battery storage investments cost reductions are expected for the upcoming years, making this technology an attractive option for DSO planners.

3.3 Curtailment of distributed generation

3.3.1 Consideration of curtailment in distribution grid planning

As mentioned before, the increased share of fluctuating energy sources makes power flows highly volatile. Considering current planning practices and the duration curve of these units as illustrated exemplarily in Figure 3-2, the network will be designed to overcome extreme loading power conditions, which rarely occur.

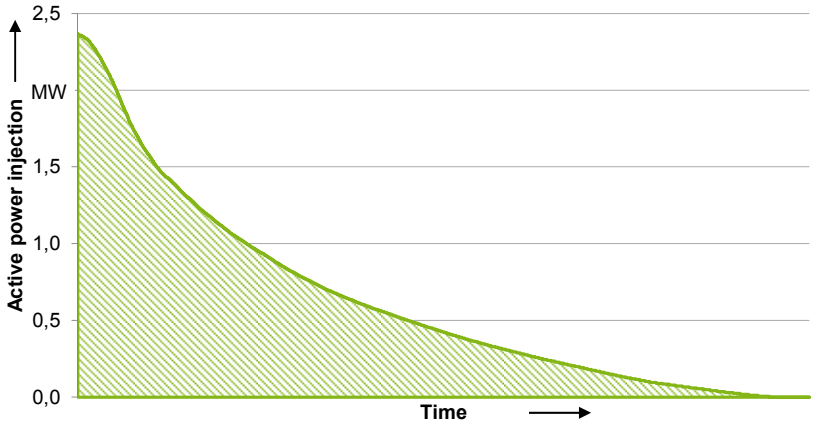


Figure 3-2: Exemplary duration curve of a 2.4 MW wind turbine in Germany

Based on the investigation the actual injected power of DG units of the same type within smaller areas like LV- and MV- networks are almost perfectly positive correlated [2]. The correlation between wind turbines and PV units is considerably smaller. If the simultaneity of load and generation is taken into account as well, typical planning scenarios (see chapter 2) almost never occur and the network will be oversized in the most cases [9] [4].The investigated correlation is derived by the analysis of over one thousand simulated times series distributed over whole Europe. In addition, a more detailed analysis with higher numbers of locations is carried out for Germany. Thereby the locations are chosen according to the Lokal-Modell Europa COSMO-EU Modell every 0.0625° latitude and longitude [14].

Curtailment of DG units can be an economic measure to reduce overloads, and hence the need of further expansion measures, without wasting too much energy. There are several ways how curtailment of DG units can be incorporated into the planning process. Since 2016, curtailment of 3 % of the annual energy generation per onshore wind turbine and per PV unit is allowed in the planning distribution grid stage in Germany [15]. Before June 2016, it was just a measure to cope with congestions during the operation. In [16], a task force proposed several approaches how curtailment can be implemented into the planning process[1]. In general, there are static and dynamic approaches.

Static approaches

Static approaches (virtually) reduce the maximum capacity of DG units during the planning process. Once the actual power of the plants exceeds a predefined limit, the power injection is cut to this point. Due to the structure of the duration curve of wind and PV units, the actual grid loading can be reduced considerably without losing much energy (3% in this case, according to [16]) as illustrated schematically in Figure 3-3.

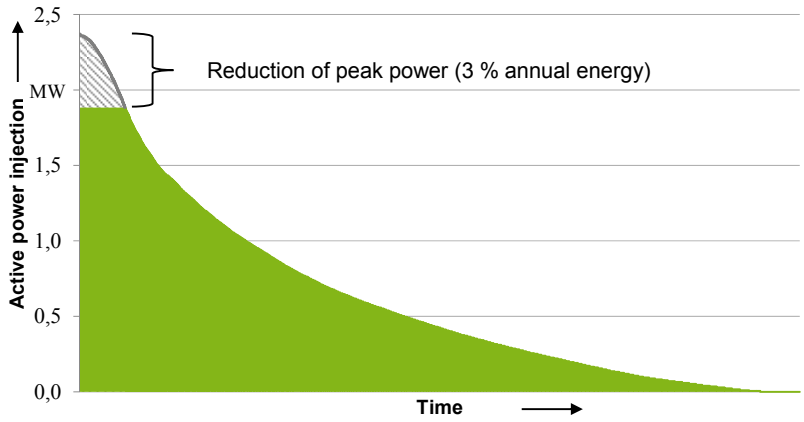


Figure 3-3: Static curtailment of an exemplary 2.4 MW wind turbine

[1] One of the Smart Planning authors was also involved in this task force

For Germany, a statistical analysis derived in [16], shows that the nominal power of wind turbines can be reduced to 87 % during the planning without sacrificing more than 3 % of the annual energy generation per unit. For PV units, the nominal power can be reduced to 70 % of the installed module capacity in the same manner. However, these factors for static curtailment can be calculated by the DSO in different ways. The different methods are summarized in [16].
The main advantage of static curtailment is its simplicity. If a static curtailment in operation is allowed by law, basically no further ICT is required. The method can be used for time series planning but also the typical worst case planning approaches can be adjusted by the calculated factors. If a static curtailment is only allowed during the planning but not during operation – as it is in Germany [15] – a sufficient number of DG units must be remote controllable to be curtailed dynamically during the operation. The main disadvantage of the static approach is its inefficiency, as units will be curtailed independently of the actual grid loading. In time steps with high feed-in and high load the curtailment might be unnecessary as the load will balance. This will reduce the potential for further time steps and lead to avoidable compensation payments.

Dynamic approaches

Dynamic approaches consider the actual grid loading before any curtailment measures are taken. Only if grid congestions are observed, DG units are curtailed, therefore planning based on time series simulation is required. In opposite to the static approach, there are typically no power limits for dynamic curtailment. As a consequence, DG units will be curtailed as much as it is required (even to zero) to solve the actual problem in the grid. Usually the DG units with the highest influence to the actual grid congestion are chosen first, but depending on the regulatory framework and the objective (e.g. equally distribution of curtailment measures vs. minimizing the overall curtailed energy) different algorithms are possible. Figure 3-4 illustrates the effect of dynamic curtailment on the DG feed-in with a curtailment of 3 % of annual energy [16].

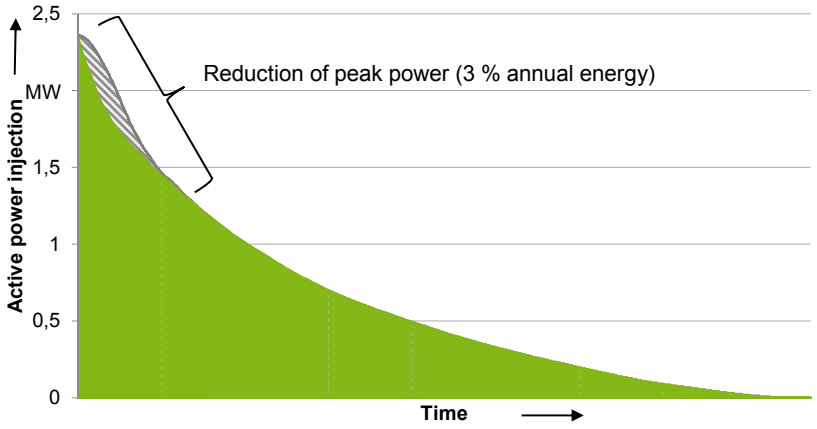


Figure 3-4: Dynamic curtailment of an exemplary 2.4 MW wind turbine

As shown, the curtailment is done at peak times but also continuous for lower active power feed-in depending on the actual grid loading.
The main advantage of this method is its efficiency, as curtailment measures are only performed to solve the actual grid congestion. On the other hand this methodology requires a high amount of ICT infrastructure as the actual grid loading and the current power injection of all relevant DG units must be measured and reported. In addition, DG units must be remote controllable to react in a reasonable time to control signals, which also requires an automated control structure. Depending on DSO already existing infrastructure and the regulatory framework, these requirements can induce a high amount of capital and operational expenditures which might reduce its efficiency. However, dynamic curtailment is currently used in some European countries as a temporary measure in grid operation, while the actual required grid expansion measures are under construction. Considering curtailment already in the planning will reduce this operational reserve.

Mixed approaches

In addition to static and dynamic approach there are several more possibilities to consider curtailment during the planning. Some could be interpreted as minor variation of the already described ones, while other might be a combination of both. However, *static* (no consideration of actual grid loading) and *dynamic* (consideration of actual grid loading) is the main feature describing curtailment algorithm.

3.3.2 Monetisation of curtailment

Obviously the substitution of conventional grid reinforcement by curtailment is not cost-neutral. Hence, its costs highly influence the investment decision. If curtailment of DG units is allowed, the plant owner will be compensated for the curtailed energy. Therefore, energy's value highly depends on the energy source, the plant size, the plant age and the remuneration system in the actual country. For instance, in Germany there are currently more than one hundred different compensations systems - depending on the aforementioned factors. Beside the costs for the curtailed energy, several additional cost components are connected with the use of curtailment. The main components are:

- Control equipment for DG units
- ICT infrastructure
- Integration of curtailment into the control system

These costs are also highly volatile and depend on several factors, like the regulatory framework, the existing infrastructure of the DSO and plant owner, the considered curtailment methodology, etc. In the literature, assumptions for the total costs of DG curtailment (capital expenditure (CAPEX) and operational expenditure (OPEX)) are usually used to validate DG curtailment. However, these assumptions highly vary (e.g. [1] [17] [18] [19] for Germany). In this study sensitivity analyse are performed to cope with this high variety.

3.3.3 Summary and recommendation

In general, curtailment is probable to be an economical alternative when network violations are caused due to high feed in of fluctuating energy sources and occur seldom over the year. Curtailment is less efficient the more often grid congestions are violated, as compensation payments rises. In the same way the benefit of curtailment against conventional network reinforcement rises the in case of less occurrence of violations. Typically, dynamic curtailment is preferred to static curtailment due to its efficiency, and hence, it should be preferentially considered in the planning. However, due to the potential high infrastructure cost for the dynamic approach, static curtailment could be the most affordable measure in some cases, especially in LV grids [20] [18]. Therefore, the existing ICT infrastructure has to be taken into account choosing the optimal curtailment strategy. Overall, curtailment should be always considered during the planning when grid congestions are induced by

DG feed in, especially in case of overloading. The economic value of curtailment is case sensitive and highly depends on the compensation payments, infrastructure costs and DG penetration level. Overall curtailment is an economic option compared to other options in case of less grid constraint violations. [20].

3.4 Reactive power support from distributed generation units

3.4.1 Consideration of reactive power management in distribution network planning

The adjustment of the reactive power of DG units can be an economic measure to regulate the voltage in the network. Currently, most units are either operated with a fixed $\cos\varphi$, or their actual flexibility is not considered in grid planning. However, DG unit support to control the voltage by reactive power is limited. This limitation can be due to the capability limits of the DG units and due to the effectiveness of the reactive power injection to the voltage based on the feeder characteristic such as $\frac{R}{X}$ ratio. For example, reactive power support is less effective if the $\frac{R}{X}$ ratio is higher (e.g. in the Netherlands) [21]. On the other hand, it might have significant impact to support voltage regulation in other countries, with a different grid characteristic. As the $\frac{R}{X}$ ratio is higher in LV grids compared to MV grids, the reactive power has relatively lower impact compared to active power on voltage in LV grids. However, it might be an economical option to support voltage regulation with the reactive power support of DG units as a first option rather than active power curtailment or conventional grid reinforcements [20]. Provision of reactive power by DG units is mainly constrained by their capacity and as well as in some countries by their

operating power factor which is for Europe usually 0.95 or 0.9 depending on the installed capacity suggested [22].

3.4.2 Methods of reactive power management

The participation of DG units in voltage regulation by managing their reactive power injections can be considered in two ways. The advanced method in which DG units communicate with the other participants in the network and adjust their reactive power support accordingly is called *centralized*. This method requires communication which has cost implications; however, this is very accurate compared to methods without communication [20]. DG units can also participate to support voltage regulation by managing their active power without communication. This is the so called *decentralized* method. There are several approaches where DG units support the voltage regulation in distribution networks without communication infrastructures; the section below focuses on the decentralized methods.

cos φ(P) method: the conventional principle is to operate the DG units with a power factor close to $\cos\varphi = 1$. Currently, $\cos\varphi(P)$ is suggested as one of the methods to help the DSO in voltage regulation. Figure 3-5 shows an exemplary characteristic curve according to which the DG units support the voltage in a feeder.

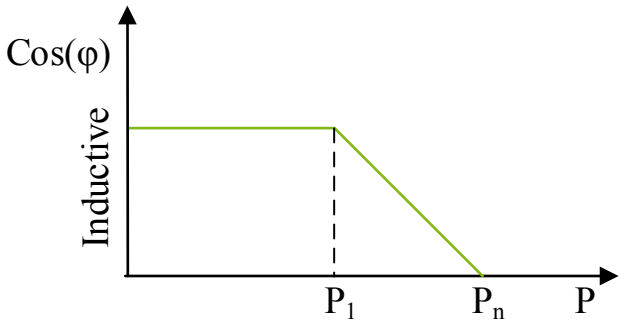


Figure 3-5: DG unit characteristic curve for ***cos φ(P)*** *method*

Reactive power support in this method is a function of the active power *P* of the unit. DG units start to operate in under-excited mode once the active power of the respective unit reaches a pre-set value of $P_1 = 0.5 \cdot P_n$. , where, P_n is the nominal power. Hence, it is assumed in this method that there would be violation of the upper limit of the steady state voltage if the feed-in of the DG unit is increased to half of its nominal value.

Q(V) method: Providing reactive power as a function of voltage at the point of common coupling (PCC) is an alternative method where DG units can participate in the voltage regulation. Reactive power is consumed/provided when there is a difference between the voltage reference value V_{ref} and the actual voltage value

V_{PCC} measured at the PCC. Figure 3-6 shows an exemplary characteristic droop function for the reactive power of a DG unit.

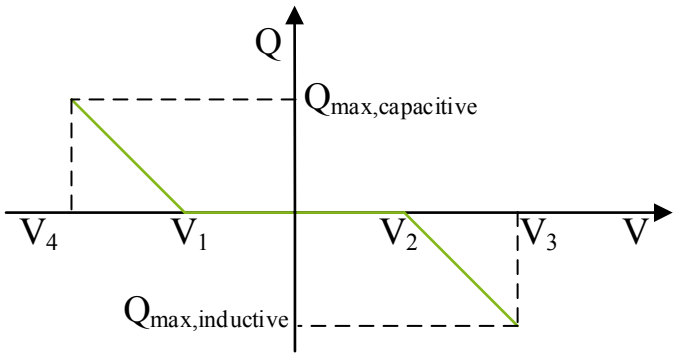


Figure 3-6: DG unit characteristic curve for $\boldsymbol{Q(V)}$ *method*

Based on the figure above, the grid-connected DG units provide reactive power at the time when there is an under-voltage problem due to the high load and less feed-in from the DG units. In the same way, the DG units consume reactive power at the time when there is an over-voltage problem due to high feed-in and less load.

3.4.3 Summary and recommendation

It is important to consider reactive power support from DG units in the planning stage. However, the effectiveness of the reactive power varies for different distribution networks.

A deeper insight into the aforementioned decentralized methods for reactive power management of DG units resulted in $Q(V)$ method being more efficient than $cos\,\varphi(P)$ method [20]. The main drawback of $cos\,\varphi(P)$ method is the assumption that the DG unit should start to support the voltage regulation in the grid once the active power of the unit is greater than half of its nominal capacity, regardless of the actual loading condition in the grid. Hence, DG units will reduce the voltage at the PCC even if there is no voltage problem. This causes many losses in the grid by unnecessarily consuming reactive power. However, in $Q(V)$ method the DG units support the grid voltage based on actual voltage at the PCC of the respective DG unit. Therefore, both actual generation and loading of the grid is considered.

The consideration of a centralized approach in which ICTs enable the DG units to communicate with other control assets in the grid would increase the overall costs. However, it leads to accurate results and in cases where there is higher penetration level of DG units in the grid, it would likely lead to less overall cost compare to decentralized approach [20].

4 Integration of smart market activities

4.1 Evaluation of flexibility potential of customers

A large part of consumer electricity usage is dependent on daily schedules and as such largely determines the resulting load profiles, independent of whether sufficient generation (or indeed grid capacity) is available. The implementation of demand side management (DSM) schemes can be used to temporally shift energy consumption to balance the fluctuating generation profile of renewable feed-in and/or relieve local grid congestions [23]. This can reduce overall system costs while simultaneously allowing for a high penetration level of renewable generation [24].

4.1.1 Analysis of European pilot results

Several (inter)national pilots address the possibilities and consequences of DSM and how to activate the flexibility in electricity use of residential consumers. Smart Planning assessed eight of these pilots (Figure 4-1) addressing flexibility in electricity use, and investigate the effects of the techniques used to activate flexibility.



Figure 4-1: Locations of eight pilots addressing flexibility.

The assessed pilots are *E-Dema* [25], *Low Carbon London* [26], *Power Matching City* [27], *Couperus* [28], *LINEAR* [29], *EcoGrid EU* [30], *Smart Charging Enexis* [31] and *Your Energy Moment* [32]. All pilots address flexibility in electricity use of residential customers. However, in each pilot different techniques are used to unlock this flexibility. Flexibility is found in wet appliances, in heating, electric vehicles, and in storage, but also in electricity use as a whole. The pilots use different definitions of flexibilities and methods to test this. In order to allow for a proper comparison the results of the different pilot projects have been standardized to a single representation. In this project, flexibility is described as a possible average change

in power, per time of day, per household. This is visualized as a possible change in load profile.

4.1.2 Observed flexibility

Looking at the total load of a current household, it is shown that increase and decrease of load occur at low and high price moments. Numerical results are shown in Table 4-1. At high price moments 30 to 110 Watt average load reduction per household is observed. Low price moments provide 20 to 90 Watt average load increase per household. More load is shifted if consumers are given more time to adjust to pricing schemes.

Table 4-1: Load shifting results of two pilots. Left [26], right [33].

	Supply following	Constraint management
Low price	+ 50 W	+ 20 W
High price	– 30 W	– 50 W
		5 - 10 % peak reduction
In general: best 25% responders perform 3 times as well		

	2-tariff product		5-tariff product	
Source	[33]	ad-justed	[33]	adjusted
ST	-	-	+ 2.3 %	+ 40 W
NT	+ 3.5 %	+ 40 W	+ 2.5 %	+ 90 W
HHT1	-	-	– 2.9 %	– 110 W
HHT2	-	-	– 0.1 %	– 0 W

Wet appliances seem to account for the flexibility in the total household load. Wet appliances provide 20 to 50 Watt average decrease of power per household (sustained for 6 hours) at high price moments and 20 to 35 Watt average increase of power per household (sustained for 6 hours) at low price moments. For short periods a maximum average decrease of power of 65 Watt, and maximum increase of 430 Watt are reported. The large amount of possible power increase is due to wet appliances giving more flexibility (in hours of postponement) than the running time of the appliance. Fig. Figure 4-2 shows a visualization of the available flexibility relative to an average consumption curve for wet appliances.

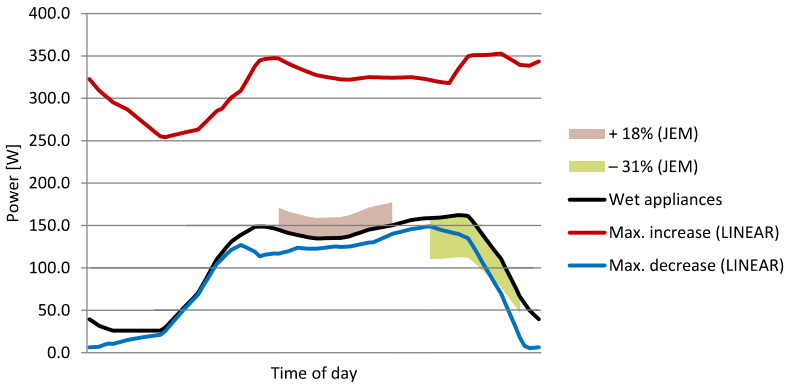


Figure 4-2: Flexibility of wet appliances. Maximum results of pilots plotted as addition to the average consumption curve. [29] [34] [32]

For heating, flexibility depends on the buffer/storage used. A larger buffer provides more flexibility. The results in this report are for a heat pump of approximately 1 kW_e with a hot water buffer of 200 L or an available temperature variation of ± 0.2°C. On average an available decrease of power of 20 to 90 Watt and an available increase of power of 30 to 120 Watt are observed. It is shown that HPs can be used for balancing and are very accurate if only a small part of the total power of the HPs is used (8%). Figure 4-3 shows a visualization of the available flexibility relative to an average heating load curve, measured in one of the pilots.

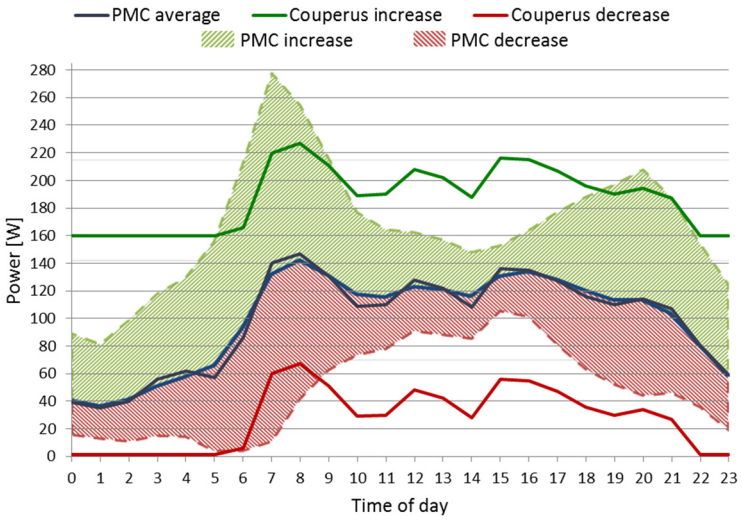


Figure 4-3: Flexibility in heating. Results of [27] and [28] plotted relative to the average measured heating profile.

Of the categories covered in this report, electric vehicles[2] show most flexibility. The EVs show most flexible power at night: –0.3 to –0.5 and +0.6 to +0.7 kW. The fewest flexible power is available at working hours, particularly around noon. The largest increase of power is available early in the morning: +0.7 to +0.9 kW. The largest decrease of power is available in the late afternoon/early evening –0.2 to –0.6 kW. Figure 4-4 shows the available flexibility over the day with respect to a flat curve at zero load.

All investigated pilots used price incentives as the way to activate flexibility. But pricing can be used in different ways, and has different effects. It is shown that using smart appliances causes more response to varying prices and provides more flexibility. As a capacity fee causes the smart scheduling functionality to be used more often, it provides more flexibility than time of use pricing. In turn, time of use pricing is more effective for load reduction. It was also seen that more load is shifted if consumers are given more time to adjust to pricing schemes.

[2] In the pilots the electric vehicles were charged with a charging power of 3.6 kW

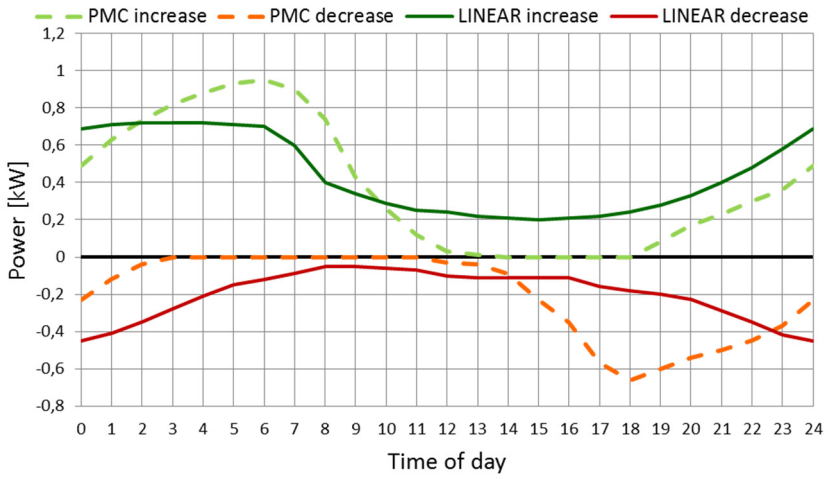


Figure 4-4: Flexibility in electric vehicle charging. Results of [29] [27], where the possible increase and decrease of power for EVs from both is shown.

To give an idea of what the total flexibility, as examined in the considered pilots, would look like if applied to a household profile, a plot is created containing all flexibilities superimposed on an average Dutch household profile [35]. For all flexibilities the minima as well as the maxima are added together; showing a minimum and maximum flexibility profile, as can be seen in Figure 4-5. The darker shaded areas represent the minimum flexibility and the lighter shaded areas the maximum possible flexibility available.

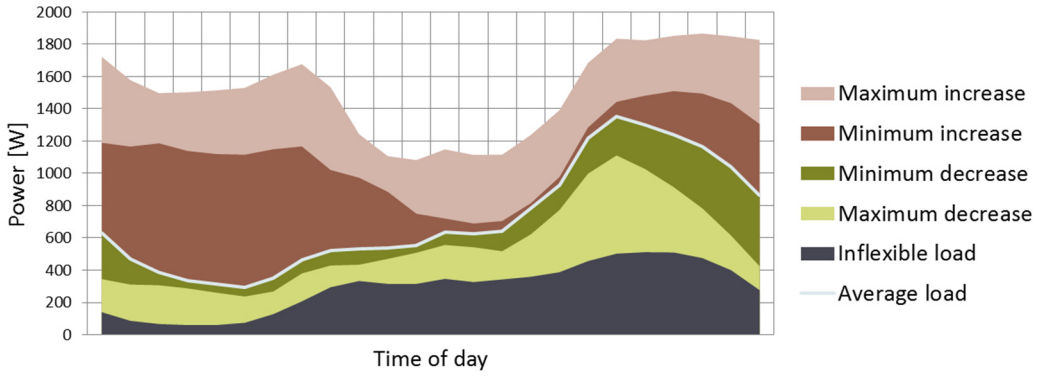


Figure 4-5: Results of flexibility plotted on top of the estimated load profile, showing the minimum and maximum increase/decrease of power possible.

4.2 Agent-Aggregator system for DSM and SSM

4.2.1 Market integration

The DER integrated in the distribution network offer the possibility for flexible operation as means to overcome the technical problems that occur from their implementation. This flexibility can be deployed by using a more active approach to manage distribution networks which includes applying DSM mechanisms.
There is uncertainty regarding the response from the system when only price reaction DSM is applied. It is possible to overcome this, if customers across all levels of the electrical infrastructure, including the distribution network, are involved in the operation of the electricity market. Considering the liberalization of the electricity sector and the new requirements for dealing with the technical challenges in the networks, there is a need for additional grid services that can be obtained through market based approach. In this context, a system of economic and control mechanisms that allows the dynamic balance of supply and demand across the entire electrical infrastructure using value as a key operational parameter is defined as *transactive energy control* [36]. By integrating DER in the market and using dynamic pricing as a control signal, the system reaction is known beforehand and the global system goal can be reached [37] [11]. This type of market based integration of DSM in the electrical power system is assessed in the Smart Planning project because of its relevance for future developments in electrical systems.

4.2.2 Market based control

Market-based control in smart electrical grids relies on application of microeconomic principles. Microeconomics studies how economic entities make decisions to allocate limited resources, usually in markets where goods or services are bought and sold. The theory of equilibrium markets is used in distributed software systems to incentivize parties to behave in a desired way. All market participants respond to the same price, the so called equilibrium price, which is determined by the balance of supply and demand of the commodity in the market [38].
Participants in the market, represented by agents, submit their demand functions, or bids, as later referred in the report, to the market. Demand function is the microeconomic term that gives the amount of a certain commodity an agent wishes to consume (or produce) given the price of the commodity. In other terms, it expresses the individual indifference for having either an amount of money of p_1 or having the commodity in an amount of $d(p_1)$, where $d(p)$ is the demand function [38].

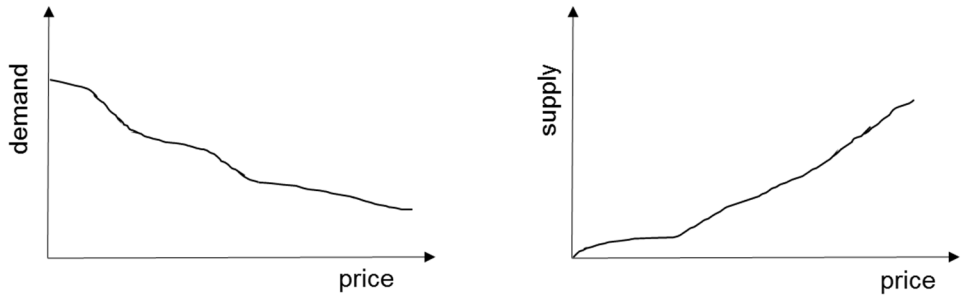


Figure 4-6: An example of demand and supply curve in a price-based equilibrium market, based on [39]

An example of a demand and a supply curve is presented in Figure 4-6. Based on microeconomic theory, demand curves are monotonously decreasing as the price of the commodity increases, whereas for the supply curves, the opposite is valid [40]. At the intersection of the two curves, the market is in equilibrium and the supply equals demand. The corresponding price, p^* as presented in Figure 4-7 is called the equilibrium price. Supply can also be presented as negative demand, as in the right graph of Figure 4-7. In this case, the equilibrium price is found at the intersection of the total curve with the x-axis.

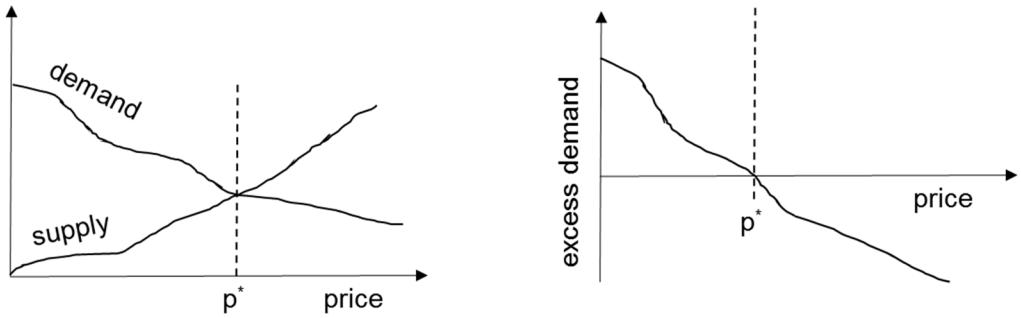


Figure 4-7: Left, Illustrative view of supply demand matching, finding equilibrium price, based on **[39]**. Right, Aggregate supply-demand curve with supply as negative demand, based on **[39]**

4.2.3 Multi-Agent system

A Multi-Agent System (MAS) is considered as a key technology to enable distributed monitoring and other control functions. With characteristics of reactivity, proactiveness, scalability and social ability, the MAS technology can offer numerous benefits in distributed power networks [41] [42].

A MAS is simply a system comprising of two or more (intelligent) agents. It is important to recognize that there is no overall system goal; there are only the local goals of each separate agent. The system designer's intentions for the system can only be realized by including multiple intelligent agents, with local goals corresponding to subparts of that intention [42]. The multi-agent approach localizes and

confines data, processing and controlling it in a bottom-up fashion, without an omniscient top-level.

4.2.4 Multi-Agent System aggregator model hierarchy

On the basis of the Power Matcher technology [38], the multi-agent system based aggregator model used in the Smart Planning project is developed. The model incorporated different types of agents as classified within the Power Matcher technology. Different devices are modelled as separate agent types and the division of the control space is considered when defining the bidding strategy of each agent. The MAS aggregator-model is structured in a hierarchical way. There are three levels of concentration in the model. The first one is on household level where the household agent concentrates the bids from all local device agents of the appliances present in that household. The second level of concentration is performed on feeder level. The feeder agent, located at the beginning of the main feeders from the substation, aggregates all bids from the household agents that are along that feeder. Finally, on the top of the hierarchy, the auctioneer agent concentrates the bids from all feeder agents, the DSO agent and the supplier agent. At this level, the equilibrium price is determined and a single scalar representing the price for that time instant is communicated back to the local device agents. The aggregator model structure is presented in Figure 4-8.

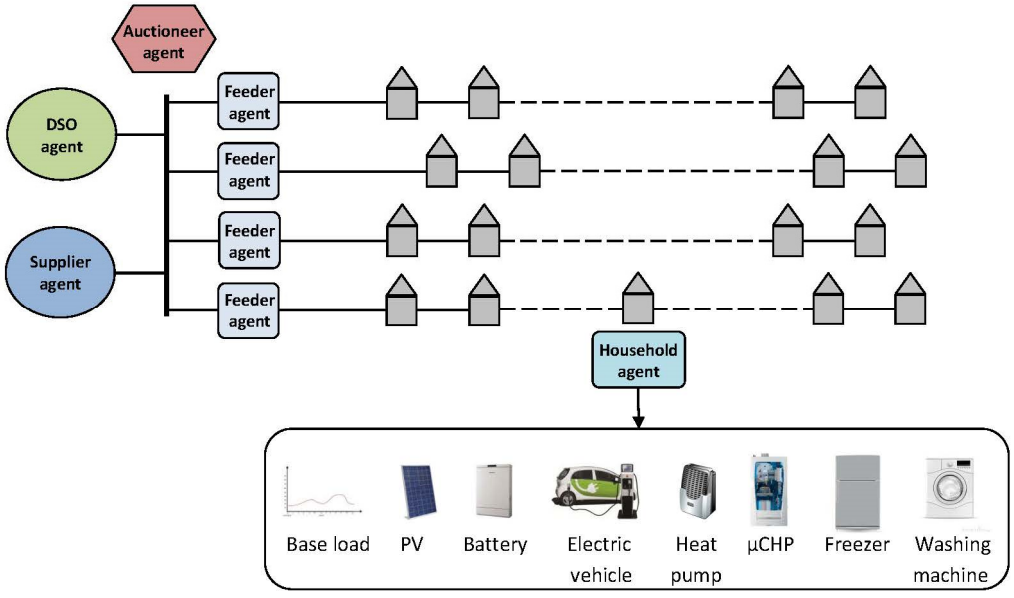


Figure 4-8: MAS aggregator model structure

4.2.5 Simulation of market strategies and scenarios

Different market strategies are applied under different load scenarios. In distribution grid planning, understanding system behaviour is important. To capture the actual behaviour of the grid, the time variability of the generation and demand profiles has to be adopted in the planning calculations. Probabilistic and time series

techniques can be used to capture the stochastic behaviour of the load profiles and generation units. Hence, the result of the grid calculations presents the equipment loading and nodal voltage stochastically. As a result the planner will have a deeper understanding of network conditions and technical limits can be shown with relative confidence in comparison to the deterministic approach by knowing not only the magnitude of the technical constraints, but also the frequency and the duration that these constraints can be violated. Furthermore, adoption of time series analysis in network calculations enables the planner to capture the operational aspects of smart distribution grids (mainly the impact of the innovative technologies and solutions) into the planning phase. These aspects should be evaluated further as viable planning alternatives by estimating and accepting the risk in contrast to conventional grid reinforcement.

For the calculations in the smart planning project, time series representation of load and generation profiles is used to present their actual behaviour. The model for time series generation of load is developed based on stochastic Markov chains as presented in [43] and the time series profile for the generation units is based on the models presented in [9] [2].

Annual simulation is performed with resolution of 15 min intervals. Thus 35 040 time samples are obtained for a yearly simulation. For every interval, the market clearing process takes place, i.e. the device agents submit demand bids, the auctioneer agents finds the equilibrium price and the devices respond to it correspondingly. The price in the simulation model is in per unit values, meaning that it has no monetary value and is used as a control signal [44]. The price vector is in the interval from 0 to 100 with resolution of 1 step. After the market responds to the price, a power flow calculation is performed for every interval to determine the network state parameters.

By adopting a time-dependent simulation, the operational aspects of different network elements can be captured [45]. Parameters that are relevant for the LV distribution system planning are reviewed and analysed. The peak power at transformer level and the maximum loading of the cables is evaluated, as well as the voltage level at the end of the feeders [46]. Moreover, a comparison is made over different market concepts to evaluate the effectiveness of DSM in each one of them in terms of peak power reduction and effect on the transferred energy. In addition, analysis of the power flow throughout the year is assessed to further investigate the effect of different DER on the grid and the possibilities for DSM. Under the *no market* strategy, no price signals are sent and all devices behave as they normally would. The *free market* strategy is an implementation of the market, where supply and demand is aimed to be matched locally and excess power is obtained from (or delivered to) the grid when required, grid constraints are not taken into account in this strategy. The *grid constrained market* functions similar to the *free market,* with additional price steering signals if grid constraints would be exceeded during normal market clearing. The *power curtailment*, finally acts as a fail-safe. Curtailing

load or generation by direct-grid control if market signals are not able to keep the power and voltage within the boundaries.

As can be seen from the load duration curves in Figure 4-9 the curves are flatter when applying any type of DSM market strategy. In addition, the differences between the different market scenarios in terms of transferred energy and average power flow are minor.

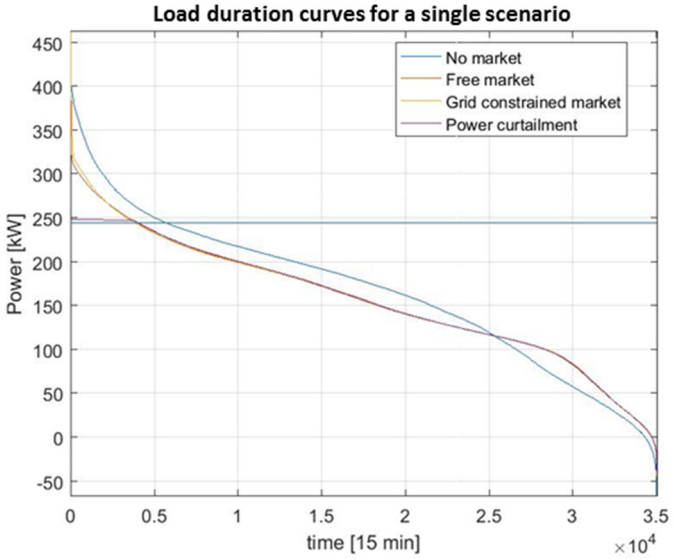


Figure 4-9: Scenario 1 – Load duration curves

In Figure 4-10, power flows of three days in the winter are presented. This scenario is load dominated and assumes a 50% penetration level of PV and EVs and a 100% penetration level of HPs. It can be seen that in the No market strategy large peaks occur in the evening times, when EV are plugged in for charging. In winter there is an additional demand for heating in the evenings, due to the heat pumps which results in even higher peaks. A significant difference between the No market and the other market strategies is because of the EV charging coordination. As the charging is arranged according to the next departure time, which is the morning, the peaks in the evening caused by simultaneous connection of large number of vehicles is partially transferred to the morning, when the departure times are set.

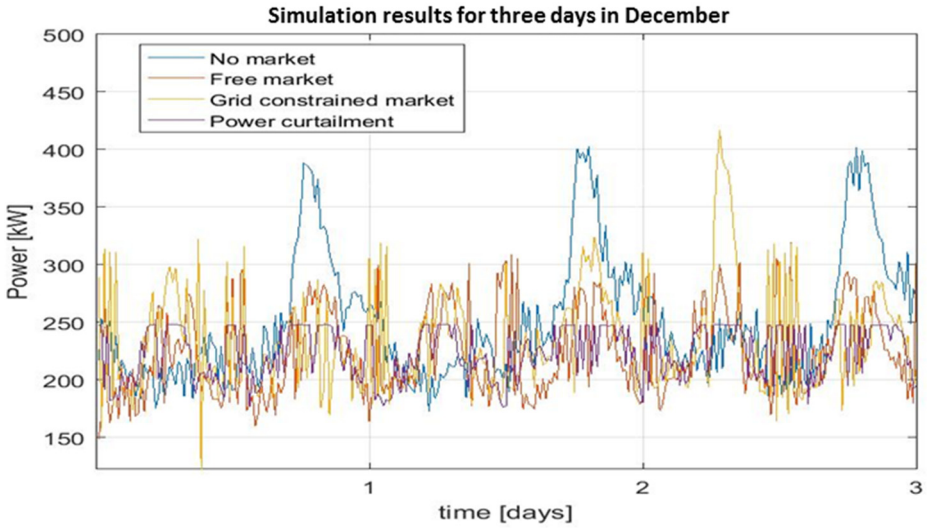


Figure 4-10: Seasonal power flows for a load dominated scenario in a Dutch LV network

The Free market and Grid constrained market overlap for most of the time, although it can be seen that there is larger power flow in the latter strategy when the flexibility allows for it. Additionally, in December, a situation when there is an isolated peak in the Grid constrained market strategy and not in the others (in the morning of day 3), can be observed. Overloadings in the network occur only in winter and spring in the three DSM based market strategies, in the evaluated study cases. Hence, only then there is need for direct grid control. An in-depth analysis of the effect of the different market strategies under different scenarios can be found in [47].

4.2.6 Summary and recommendations

Different load scenarios and market strategies were tested on several representative LV grids, both rural and urban. It is observed that implementing a market strategy significantly improves the impact on the grid in comparison to having no market. In resilient networks that can sustain large penetrations of DER or in networks where there is a high level of local production of electricity, just the implementation of a market will be sufficient to resolve problems. Implementation of market strategies where the DSO can additionally deploy flexibility for grid services either through market participation or direct control can further improve the operation of the networks. However, the extent to which this can be done is dependent on the available flexibility in the networks. When there is very little flexibility available, the DSO cannot significantly reduce the impact of occurring congestions and can even result in shorter but higher overloadings.

Based on the cost benefit analysis, the DSO will note savings due to the reduction of costs for the technical losses in the network but will on the other hand have additional costs for deploying DSM. To implement DSM as an alternative in network planning, the savings from reduction of technical losses and the additional

costs for DSM should be compared to the grid reinforcement alternative. Depending on the actual implementation of a market framework, the choice between DSM and grid reinforcements can be evaluated. By using market based DSM strategies there is a possibility for deferring grid investments to a certain extent, however specific costs and benefits are very case and scenario dependent.
For instance in the urban network, the total costs for the DSO are reduced in all scenarios due to a reduction in technical losses caused by the flattening of the load profile [47], without even factoring in the deferral of the investment in a new transformer. However in all networks the load dominated scenario showed an increase in average customer electricity costs, which off-sets the DSO benefits when looking from an overall system perspective. Conversely, in the scenarios with more local generation, the customer electricity costs were also lowered.

5 Optimal planning of future distribution grids

5.1 Description of the optimization tool

In this part, a planning procedure is proposed which considers both conventional expansion measures, e.g. upgrade of transformers and cables with ones of higher capacity, as well as smart options, such as OLTC, active and reactive power control of distributed generators, and smart technologies such as battery energy storage systems and flexible loads. At the core of the proposed decision making process lies a tractable iterative optimal power flow method based on the Backward - Forward Sweep (BFS) approach, shown in Figure 5-1.
Smart Planning project presents a decision-making tool which co-optimises investment and operational decisions in distribution grids. As investment decisions, the installation of grid upgrade measures including new branches (cables or transformers) and battery energy storage systems (BESS) are considered. The considered active measures include dynamic APC, Reactive Power Control (RPC) and Controllable Loads (CL). These fall into the category of investment deferral measures, all of which incur operational cost to the DSO. An iterative AC OPF formulation, based on the backward-forward sweep technique [48], [49], is adapted and extended to consider both conventional upgrade options and active measures, transforming the problem into a mixed integer linear program (MILP). This formulation captures combinations of conventional grid expansion measures with control of DERs, and includes the inter-temporal constraints of BESS and CLs. In this work, it is assumed that there is no regulatory framework imposing a certain planning procedure to the DSOs. That way, in case the security of supply is not endangered, a DSO can choose freely among conventional grid expansion methods, active measures, or a combination of both.

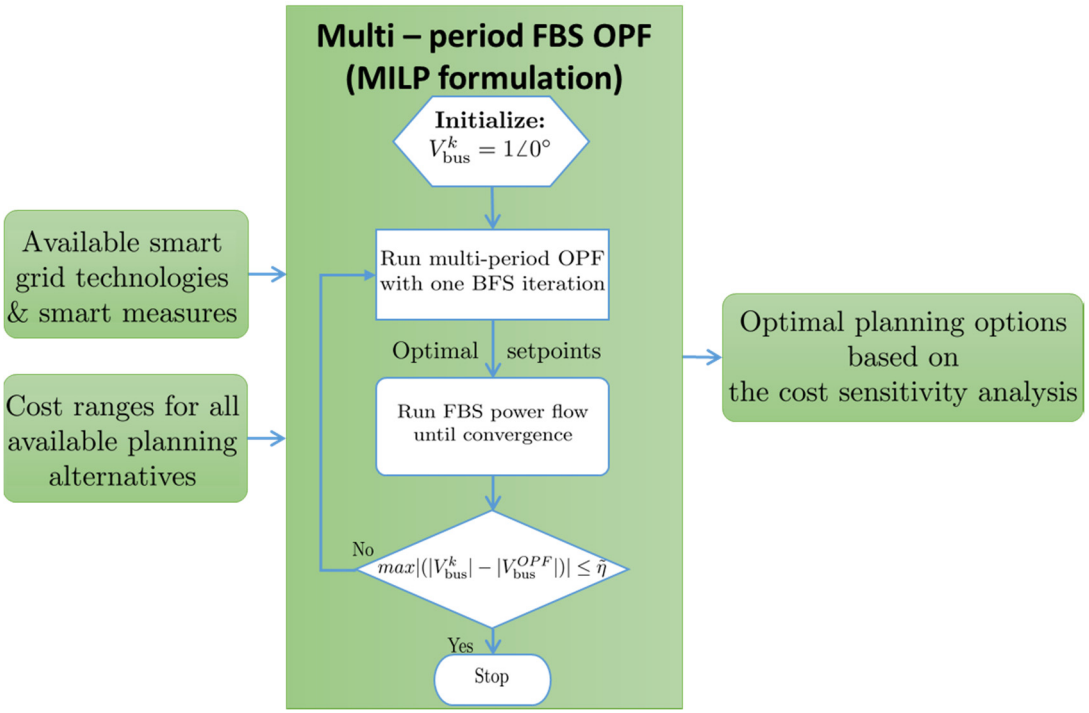


Figure 5-1 Proposed multi-period OPF based on BFS approach [50].

The main idea is to form one optimization problem in order to minimize both the investment and the operation costs. The reader is referred to [48] and [50] for a comprehensive modelling description of the optimization formulation.

Problem Formulation:
Derive optimal investment strategy so as to minimize jointly the OPEX and CAPEX, based on a multi-period BFS – OPF.

$$\text{minimize } (c_{inv}^T Z + c_{op}^T u) := CAPEX + OPEX$$

Subject to:

- Power balance
- Voltage limits
- Thermal loading limits
- DER limits
- Controllable load constraints
- BESS dynamics

Looking at the objective function in more detail, variable Z corresponds to hardware installation, be it transformers, cables or BESS, and u is associated with operational costs of active measures, such as dynamic APC, centralised RPC or CLs. As constraints, the power balance, voltage and thermal limits, the DER constraints and the dynamics of the CLs and BESS are considered. Finally, since components with different lifetimes are compared, the Equivalent Annual Cost (EAC) is used so that the comparison makes sense [51]. In this work, distribution grids with reliable communication infrastructure are assumed, where all measurements are gathered at the DSO and a network-level optimization is used to compute the system-wide, optimal, DER setpoints.
The optimal decision is case-dependent and varies from area to area. The driving factors which define the best DSO actions are the investment and operating costs. These can be very different even within the same country, depending on where the installation will take place as well as on additional cost, e.g. installing a cable in the centre of Zurich is much more expensive than in a rural area.

Table 5-1: Cost ranges of DSO planning options

			Lifetime (y)	Cost	Projected cost evolution	Sensitivity analysis ranges
Planning options based on:	investments	Cable	40	€/m	stable ≈	50-150 €/m
		Transformer	20-40	€/kVA	≈ ↓	Fixed
		BESS	5-10	€/kWh	↓ ↓ ↓	600-200 €/kWh
	operational control	APC	-	€/kWh	policy, regulation ↓ ≈ ↑	0.1-0.4 €/kWh
		RPC	-	€/kWh	negligible	fixed, linked to C_{APC}
		CL	-	€/kWh	load nature, regulation	fixed

In order to show the influence of the cost on the optimal results, a sensitivity analysis is performed, varying the most important cost units. Table 5-1 shows the costs and their assumed range of the different planning options, depending on the location, policy and the maturity of the technology. The used values are derived by an extensive survey among several DSOs of several European countries.

5.2 Additional investigations

In the following section, a summary of additional investigations regarding the reliability of active distribution networks and the future role are presented.

5.2.1 Cost-Reliability Analysis of different Automation and Protection Configurations

As part of Smart Planning project, a cost-reliability tool is developed [52]. The key focus of this study was to analyse how changes in the protection and/or automation layer of a certain distribution network influence the system reliability and the total costs for the utility. Therefore, two systematic tools that could be used in the future by DSOs as planning techniques for new automation and/or protection configurations were presented. The first one, the cost-reliability assessment tool, deals with the calculation of costs and reliability indices for a specific distribution network topology with a unique automation and protection configuration. The second tool searches for the optimal automation and protection configurations for a given distribution network topology.
Both tools were used for conducting two different types of case studies. The first case study compared nine different protection and automation concepts for a typical medium voltage ring topology of ewz. The second case study on the other hand, dealt with the comparison of two specific different protection and automation configurations of a real distribution network within the city of Zurich.
In general, it can be concluded that the system reliability of a medium voltage ring increases significantly with a relative low impact on the costs by adding full automation to one specific secondary substation. However, adding automation to more secondary substations results then in a more considerable cost increase for a relatively low impact on the system reliability. The interested reader is referred to [52] for a detailed modelling description.

5.2.2 Pricing mechanisms for active DSOs in Distribution Networks with High Penetration of Flexible Prosumers

Instead of pursuing costly investments for the network reinforcement and expansion, the system operators could consider various options based on the local unit control. Features such as decentralized battery energy storage, photovoltaic curtailment, dynamic demand response, on-load tap changers and reactive power control could aid this cause and are therefore included [53]. An additional market perspective could be facilitated through modelling of new pricing concepts which have a profound impact on the final consumer behaviour.

In the developed software tool which is described in detail in [53], the cost-effective analysis of modern smart grid features, as well as their integration into the distribution network was conducted. The key focus was to investigate new comprehensive planning guidelines from several perspectives (grid, market and customers) and combine them into a unique solution for resolving potential voltage and loading issues. For this purpose, a universal software tool was developed that enables a comprehensive analysis and optimization of distribution grids and various pricing schemes.
The results of this work show that under current conditions, a penetration of full PV potential in the observed LV network would invoke drastic voltage and transformer loading problems. While the share increase in smart grid technologies on the local level aids the stresses in the system, it is insufficient for keeping all critical values within predefined boundaries. However, an introduction of a novel pricing mechanism can improve the current customer incentives and eliminate the need for reinforcement and potentially over-dimensioning the network. It has been proven that volumetric grid cost schemes, where the grid costs are calculated per consumed energy, are highly ineffective in addressing the high PV in-feed sequences, and the capacity-based approaches have thus been introduced. Furthermore, the sensitivity studies indicate that new computational methods of electricity rates should be taken in order to fairly address the utilization costs in modern smart grids.

6 Case studies

6.1 Case studies analysis

In order to consider different typical MV and LV European grids, the proposed planning methodology is applied to two LV and two MV case studies.

6.1.1 LV Urban Grid - CIGRE LV benchmark grid

Figure 6-1 shows the considered urban LV grid equipped with 4 PV units, based on a typical European configuration. Figure 6-2 shows the optimization optimal planning results, and the DSO EAC with the unit costs / prices varying according to Table 5-1.

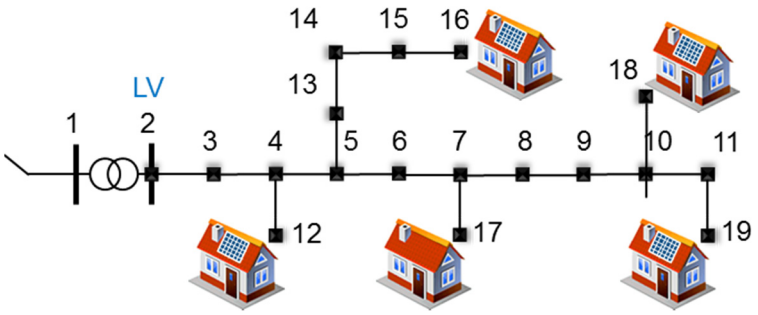


Figure 6-1: Cigre benchmark LV grid [54]. Cable length 4-12 increased by a factor of 3 in order to drive a case where grid constraints are violated

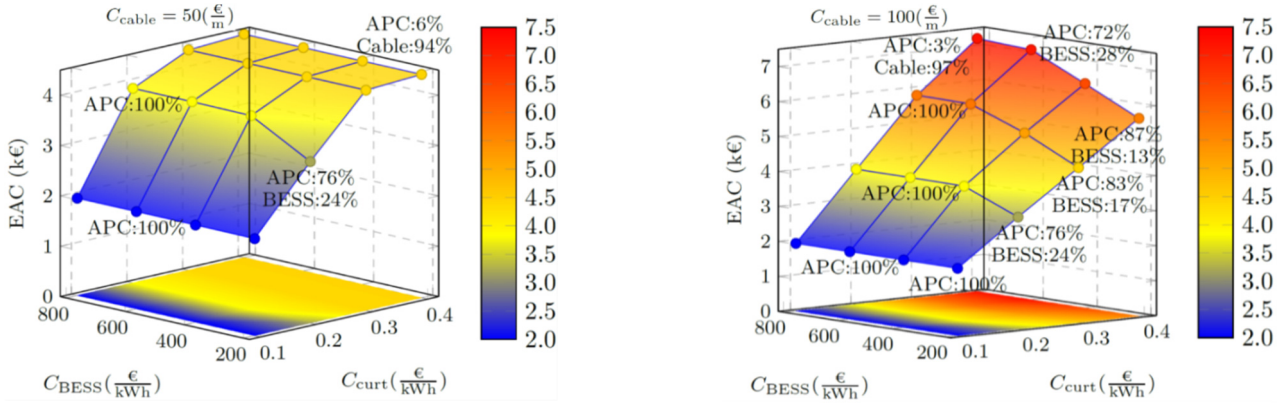


Figure 6-2: DSO Equivalent annual cost for $\boldsymbol{C_{cable} = 50 \frac{€}{kWh}}$ (left) & $\boldsymbol{C_{cable} = 100 \frac{€}{kWh}}$ (right)

Thus, it can be identified in which ranges, different planning options are the most cost efficient. The numbers at the vertices show which percentage of the EAC (the value of which is shown using the colour map) is spent on each planning option. In all cases, centralised RPC is always used, due to negligible costs. In the optimization procedure, the RPC cost represents a small penalty on the control effort. For both cases, low curtailment cost ($C_{curt} \leq 0.2 \frac{€}{kWh}$) indicate dynamic APC as the most preferable option (used to 100%). As this cost increases, other measures are also utilized, e.g. BESS if they are cheap ($\leq 200 \frac{€}{kWh}$) or an additional cable when $C_{curt} \geq 0.3 \frac{€}{kWh}$, as depicted in Figure 6-2 for which $C_{cable} = 50 \frac{€}{m}$. For higher cable cost, dynamic APC and BESS are used almost in all cases.

6.1.2 Meshed LV Suburban Grid

Figure 6-3 shows the topology of the considered meshed LV grid. Looking at optimal results in Figure 6-4, it can be concluded that for this test grid, cable installations, centralised RPC (with negligible costs) and dynamic APC yield the cheapest solution.

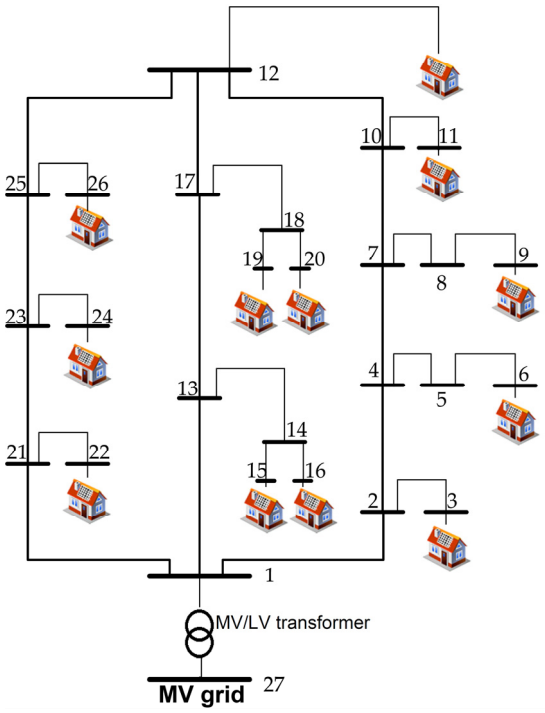


Figure 6-3: LV suburban grid topology

BESS are used only when APC is very expensive, whereas the transformer is not exchanged in this case. Increasing the cable cost results in less conventional expansion measures, when dynamic APC is cheap.

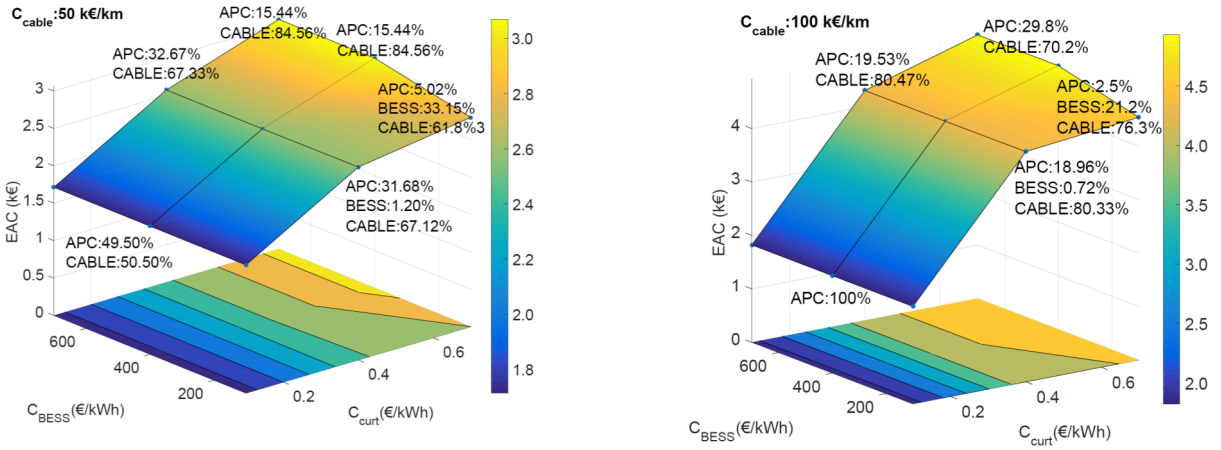


Figure 6-4: DSO Equivalent annual cost for $\boldsymbol{C_{cable} = 50 \frac{€}{kWh}}$ (left) & $\boldsymbol{C_{cable} = 100 \frac{€}{kWh}}$ (right)

6.1.3 MV Rural Grid - CIGRE MV benchmark grid

Figure 6-5 shows the rural MV grid with the assumed installed DERs. Figure 6-6 shows the optimization results for this case study. It can be concluded, that APC is used almost 100% (together with RPC which has negligible cost).

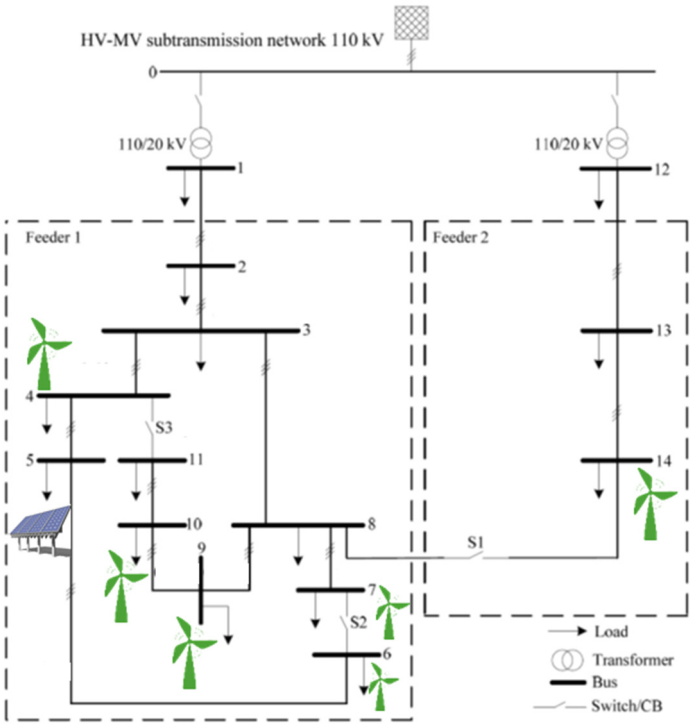


Figure 6-5: MV Rural grid topology [54]. All line lengths were increased by a factor of 3 in order to drive a case where grid constraints are violated.

This is happening because of the heavy overvoltage issues in absence of any control measures. On the one hand, the distance of the cable is long, making the conventional expansion rather expensive. On the other hand, installing BESS would not solve the overvoltage problem, since the required capacity would be extremely large.

Overvoltages occur during whole summer days, and the BESS cannot have a proper daily cycle, i.e. they would need to charge for many hours. Setting the voltage limit to 1.1 p.u. does not change the results dramatically. In presence of a transformer with OLTCs (with steps of 2.5% p.u.), the voltage issues would have been solved. However, exchanging the transformer with one with OLTC capabilities is not the optimal cost-efficient planning option.

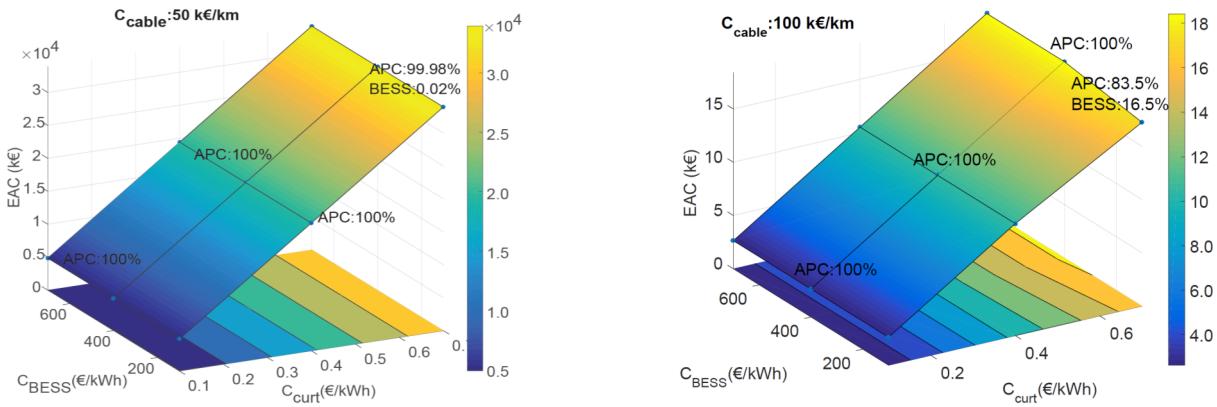


Figure 6-6: DSO equivalent annual cost for $\boldsymbol{C_{cable} = 50 \frac{€}{kWh}}$ & $\boldsymbol{V_{max} = 1.04\ p.u.}$ (left) and $\boldsymbol{C_{cable} = 100 \frac{€}{kWh}}$ and $\boldsymbol{V_{max} = 1.1\ p.u.}$ (right)

6.1.4 MV Urban Grid - 31-bus MV grid

Finally Figure 6-7 shows the topology of the urban MV grid, with Figure 6-8 showing the corresponding optimization results for this MV test grid.

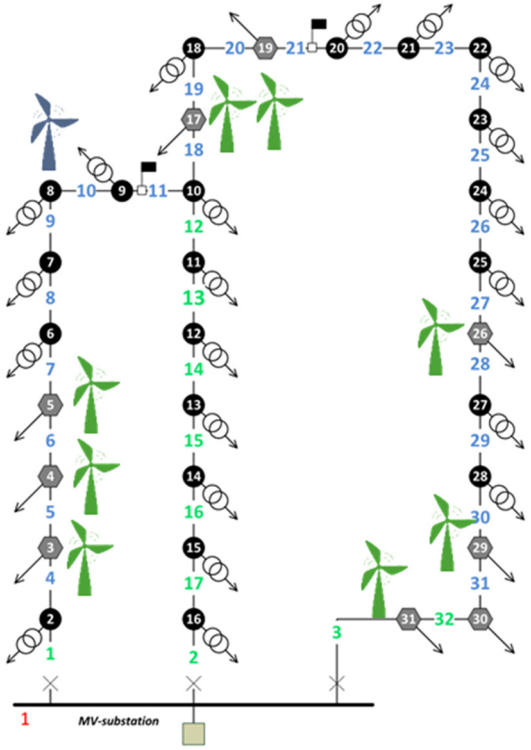


Figure 6-7: 31-bus MV Urban Grid

It can be observed, that only cable installations, RPC and APC are used in the optimal solution. This can be explained by the thermal overloading of 3 cables in the case without any control measures.

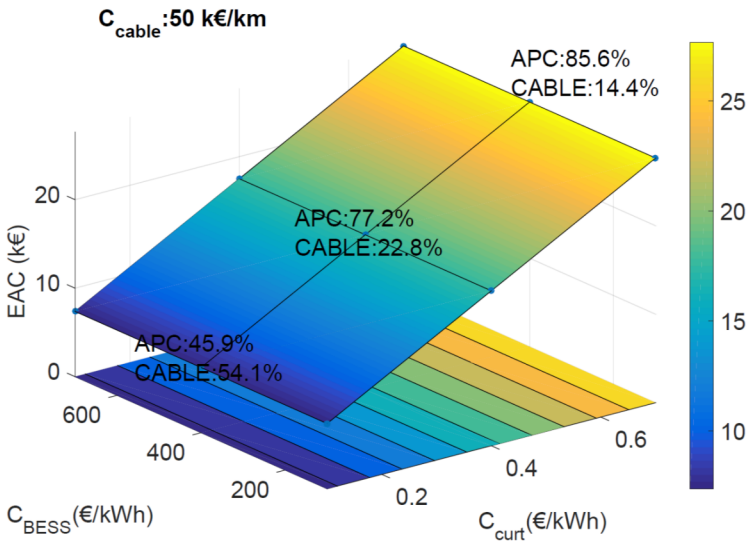


Figure 6-8: DSO Equivalent annual cost for $C_{cable} = 50 \frac{€}{kWh}$ and $V_{max} = 1.04\ p.u.$

6.2 Summary and recommendation

DSOs have nowadays a variety of tools in their disposal to face the planning and operational challenges of the future. These include both conventional expansion decisions as well as smart options. For different study cases, the most cost efficient planning option is identified. To account for different costs at different places, a sensitivity analysis is performed, varying the most critical costs.

The scope of Smart Planning was to simulate different typical LV and MV European grids in order to get an intuition on the optimal planning strategies for Europe. Overall, it can be concluded that the optimal planning decisions are case dependent and modern DSOs need sophisticated tools capable of co-optimizing and combining conventional grid expansion and active control measures.
By analysing the results, one can make the following observations:

1. LV grids: short distance of cables favours the conventional upgrade/exchange combined with reactive power control and active power curtailment when there is excess production by distributed generation. Battery energy storage systems will become attractive as their cost decrease, or in case of a potentially increase in the costs of other active measures. For larger cable distances, it makes more economic sense to rely mostly on active measures, i.e. active power curtailment and battery energy storage systems (assuming low investment costs for BESS).

2. MV grids: The distances among the different nodes are longer than in the LV case, and thus, the direct control measures seem more suitable to make sure that all network constraints are not violated. Wind power does not follow the typical daily patters of the photovoltaic power of the LV grids, and that does not favour the installation of battery energy storage systems, whose capacity should have been very large. The use of transformers equipped with On Load Tap Changers can solve most of the overvoltage issues arising from high distributed generator penetration.

7 Recommended planning guidelines

In the Smart Planning project the impact of smart grid technologies, smart grid measures and smart market activities (together smart options) were investigated as alternative planning options in distribution networks. The considered options were already part of research, pilot projects and case studies for several years and its beneficial impact on particular girds has been proven in the past. Based on these investigations and additional analysis Smart Planning move one step forwards and transfer the results into generic planning guidelines, which should help the planner to consider smart options during the distribution network planning process. Some of the results are expected, while others contributed as an added value to the development of a generic planning guideline for distribution networks. The following recommendation are general hints in order to find the most efficient expansion of distribution networks but cannot replace a detailed planning by the DSOs as distribution network planning is highly case dependent.

General Recommendation

- The smart planning project has shown that conventional grid expansion will still be necessary in the future. However, by combining it with smart options at the right time, Distribution System Operators (DSOs) can optimize their expenditures.
- Information and Communications Technologies (ICT) will play an important role as one of the main factors enabling the flexibilities. In order to plan smart, DSOs would benefit from getting access to the building's management system. To achieve that, a proper interface and potentially a monitoring system are also necessary. However, the reliability and cost of ICT should be justified and reflected precisely in the planning stage.
- To capture the behaviour of the network, the time variability of the generation and demand profiles has to be adopted in the planning calculations. Probabilistic and time series techniques should be used to capture the stochastic and volatile behaviour of loads and generation units. Hence, the result of the network calculations should presents the asset loading and nodal voltage stochastically.
- In smaller geographical regions, there is a high correlation between the feed-in of each individual type of intermittent DG unit. Therefore, especially for the wind turbine the time series of one generator can be considered relatively representative for other generators of the same type in the same region if implementation of measurement is costly. However, for PV-units pollution and clouds can lead to different local behaviours.

Smart Grid Technologies and Measures

- The costs for Line Voltage Regulators (LVR) and On-Load Tap Changers (OLTC) can be slightly lower in comparison to conventional grid reinforcement. However, the final decision of choosing these options depends on grid

characteristics such as the arrangement of the feeders, voltage level, and load/feed-in distribution.

- Battery energy storage systems proved to be an expensive option, but a considerable investment cost reduction is expected for the next years
- Active power curtailment and reactive power support of DG units are in general preferable planning options.
- Active power curtailment is an efficient measure to solve both overloading problems as well as overvoltage issues. However, since it is frequently linked with operational costs, reactive power control is prioritized to cope with both under- and overvoltage's mainly in networks with high $\frac{R}{X}$ ratio.
- If the grid constraints are violated rarely, active power curtailment and reactive power support of DG units are likely the most economic options compare to the other planning options
- Dynamic active power curtailment of DG units is more efficient than static active power curtailment, but requires ICT infrastructure. Depending on the cost of ICT, static approaches might be more preferable.
- Reactive power support of DG units based on $Q(V)$ method is more efficient than $cos\ \varphi(P)$ method.
- Centralized coordinated reactive power support of DG units is more efficient than decentralized reactive power support, but requires ICT infrastructure. Depending on the cost of ICT, different distribution control approaches might be more preferable.

Customer Flexibility Potential

- The flexibility currently available in households mainly comes from white goods and is limited with respect to the amount of power that on average can be shifted. The flexibility potential is however expected to grow substantially with an increasing penetration of electric vehicles and heat pumps which are shown to have a large potential for load shifting in real life setups.
- The use of smart appliances, which can (semi-)automatically respond to time-varying prices, provides more (and more reliable) flexibility than manual response.

Smart Market Impact

- Implementation of a local smart market, with the goal of balancing of balancing locally supply and demand, can substantially reduce peak loading in the grid and thereby defer the need for grid investments.
- In distribution networks with a large amount of generation, implementation of a local market will be more attractive than in load dominated networks, as the availability of local generation leads to a more effective operation of the market. An effective market results in lower average prices and a larger reduction in peak loading.
- Implementing market strategies where the DSO can additionally deploy flexibility for grid services improves the operation of the networks, by resolving

congestion. But to ensure grid robustness, a fail-safe mechanism should also be in place, e.g. in the form of direct grid control, as the market may not always be able to clear itself within the grid constraints.

- There are still many uncertainties and restrictions, hindering the integration of a local smart market as a reliable long term planning alternative. Most notably, the willingness of customers to participate in such markets, the reliability and security of the necessary ICT infrastructure, and the regulatory changes required to operate such a market and allow DSOs to participate to some extent.

Combined Smart Options

- In LV grids with short cable distances, the conventional grid reinforcement combined with active power curtailment by DGs, as well as reactive power control might comprise the most cost-efficient combination among the planning options. Battery energy storage systems will complement PV units and will become attractive as their cost decrease, or in case the other available active measures become expensive due to regulation.
- In MV grids, the distances among the different nodes are larger than in the LV case, and thus, the direct control measures seem to be the most economic planning alternatives. Wind power, not following specific typical daily patterns, does not favour the installation of battery energy storage systems, whose capacity should be very large. The use of transformers equipped with OLTCs can solve in an economical way most of the overvoltage issues arising from high distributed generator penetration.

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