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New role of smart metering in grid planning, control and operation

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Working Group

Final Report

New role of smart metering in grid planning, control and operation

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Note:

Figures presented in this report have been collected from the referenced documents.

List of abbreviations

ANN	Artificial Neural Network
AMI	Advanced Metering Infrastructure
AI	Artificial Intelligence
CAPEX	Capital Expenditures
CBA	Cost Benefit Analysis
CSG	Chinese Southern Power Grid
CIM	Common Interface Model
DCU	Data Concentrator Unit
DER	Distributed Energy Resources
DG	Decentralized Generation
DMS	Distribution Management System
DR	Demand Response
DNO	Distribution Network Operator
DSR	Demand Side Response
DSO	Distribution System Operator
EV	Electric Vehicle
FDIR	Fault Detection, Isolation and Recovery
GIS	Geographical Information System
GDPR	General Data Protection Regulations
HAN	Home Area Network
HIF	High Impedance Faults
HV	High Voltage
IED	Intelligent Electronic Device
IHD	In-Home Display
IPQMS	Integrated Power Quality Monitoring System
IT	Information Technology
LV	Low Voltage
MDM	Meter Data Management
MDMS	Meter Data Management System
MGA	Modified Genetic Algorithm
MID	Measuring Instruments Directive
MV	Medium Voltage
OLTC	On Load Tap Changer
OMS	Outage Management System
OPEX	Operational Expenditures
PLC	Power Line Communication
PLL	Phase-locked loop
PQ	Power Quality according EN 50160
PV	Photovoltaic
RMS	Root Means Square
RTU	Remote Telemetry Unit
SCADA	Supervisory Control and Data Acquisition
SOM	Self-organized Map
SVM	Support Vector Machine
TSO	Transmission System Operator

2 INTRODUCTION

2.1 BACKGROUND

European decarbonisation goals are massive drivers for power system planning, control, and operation changes. In addition, technical developments in data analytics and information technologies enable new use cases. Pushed by the goals of the European Union in the field of electricity metering, the so-called "smart meter" have been and will be further rolled out all over Europe. While the main application of these meters -provided by the meter manufacturing and IT companies- lies in the automation of electricity metering processes themselves, the comprehensive smart meter rollout offers possibilities for the distribution system operators (DSOs). The extensive collection of (real-time) data especially calls for using them to optimise the processes in planning, control and operation of distribution grids. According to the different national legal frameworks in many countries, data acquired with smart meters are owned by the customers: where this is the case, customers can refuse access to the data by others, including the DSO.

2.2 SCOPE

The Working Group consists of two representatives of grid operating companies of different sizes to identify the relevant processes to be improved by smart meters and experts from vendors of smart meters to match the processes according to meter functionalities.

In detail, the Working Group handled the following tasks:

- Analysis of ongoing smart meter rollout projects all over Europe to identify common/minimum/maximum smart meter functionalities, the smart meter infrastructure including the telecom network, and lessons learned from the projects.
- Analysis of distribution grid operators' processes to be potentially improved in the categories
    - distribution grid planning
    - distribution grid management
    - distribution grid control
- Definition and description of the main use-cases (process-optimisations) achieved by smart meters and metering infrastructure in distribution grid companies
- Analysis of the trade-off between process optimisation in the main use-cases, smart meters' functionalities, metering infrastructure and associated costs.
- Identifying opportunities to improve and standardise enhanced smart metering functionalities and technical specifications.

2.3 AIM OF THIS REPORT

The final report displays state of the art and perspectives offered by smart meters to improve distribution grid operators' processes, especially in planning, control, and operation. The report also covers telecommunications and data management associated with smart-meter data gathering and treatment. On this topic extended by requirements and recommendations in the fields of Information Technology (IT), the main Reference is CIGRE technical Brochure C6/D2 "Utilisation of data from smart meter System" [1]. The major aim of this report is to identify further use cases in respect to the "New Role", which can be established independently from the detailed technical design of the meter and related infrastructure, on the one hand, and to identify gaps and recommend solutions for closing these gaps, on the other hand.

3 DISTRIBUTION SYSTEMS

Safety, quality of supply and tariffs/regulation are the framework of distribution grid operation. Customers and other electricity market participants expect the maximum achievable quality at a minimum of tariffs. The definition of both parameters and their ratio is dependent on the economical and social context and, therefore, it varies between the countries even within Europe. Thus, many countries have installed respective regulatory bodies.

3.1 DISTRIBUTION GRID PLANNING

DSOs have to elaborate long-term forecasts regarding load and generation for network planning. The fitting of the network traditionally requires a 100% capacity to fulfil the customer's requirements. Due to decentralised generation (DG), especially from renewable energy resources, self-consumption optimisation strategies, and the impact of liberalised electricity and flexibility markets, forecasting became more and more challenging.

Forecasting is based on any available customer information. Smart metering data (15-minutes-profiles) merged with other personal information regarding age, behaviour and lifestyle would be helpful to make more accurate forecasts. Restrictions regarding privacy in many countries are blocking or strongly limiting the use of such data without explicit agreement. Data privacy obligations, including those imposed by the EU General Data Protection Regulation (GDPR), have been seen to pose a challenge when optimising the return on investment in smart meters.

3.2 DISTRIBUTION GRID MANAGEMENT

The distribution grid assets, the use of the public grid, and its hosting capacity require effective management. Any surveillance system collecting data regarding outages and voltage quality or imbalance provides views on the grids about critical nodes. Such systems can support optimising the grid and decision-making within asset management. From a technical point of view, the potential benefits may be high, but the total cost of installation, maintenance and operation of such a surveillance system may also be high. Smart meters with enhanced functions as sensors, like "eyes in the grid", could become a part of a positive benefit/cost system.

Power Quality (PQ) has been an acknowledged problem in the power system for decades.It is finding renewed interest from the utility community due to the changing generation and consumption dynamics. The generation segment is disrupting the traditional discipline due to unprecedented growth in renewable sources at different voltage levels. However, the biggest challenge in PQ comes from the power electronics devices involved in renewable generation. These devices can add a lot of harmonics to the grid if appropriate filters are not used. The consumption behaviour also observes a wide transformation due to unsynchronised loads added at multiple entry points and voltage levels. Some further examples of the same effect are electric vehicle chargers that range from few tens of kW to hundreds of kW, a host of data centres equipment, ventilation, air conditioning devices, arc furnaces that run by variable frequency drives, switching converter circuits that not only add a lot of unwanted harmonics to the grid but are also responsible for voltage sags, transients, leading to short and long interruptions, brownouts, flickering. Small domestic loads, such as LED lamps, laptops, phone chargers, which have unusual power factor distribution to reduce the active power, can also cause PQ problems.

3.3 Distribution grid control

The network topology consists of meshes operated in closed (high) or open (medium voltage) loops in a distribution grid with good reliability. Therefore, most customers can stay supplied during maintenance or extension works in high voltage (HV) and medium voltage (MV) grids. Instead of manual operation of source breakers at HV/MV substations, remote control is included in most medium voltage systems. Faults detection, isolation, and restoration (FDIR), can be improved by an increased level of remote sensing and automation and, therefore, reduce outages' frequency and duration.

Automatic Voltage control systems with on-load tap changers (OLTC) in transformers are typically installed in grid and primary substations to help optimise the medium voltage busbar level. In comparison, the MV/LV transformers may included off-load tap settings that can only be changed during an outage.

All functions are typically implemented as part of a central SCADA/DMS (Supervisory Control and Data Acquisition/Distribution Management System) system for HV and MV networks.

At low voltage (LV) network level, the need for hosting more capacity as well as load flexibility resulting from the increasing number of rooftop installations of photovoltaic (PV) units as well as electric vehicle (EV) charging stations have initiated the development of LV automation including voltage control systems. The affordable implementation of LV networks to SCADA systems or similar ones is discussed. Smart meters could act as intelligent electronic devices (IED) and be used for real-time applications, long term monitoring or even as an interface to home area networks (HAN) for demand response (DR).

4 References

The working group collected around 130 references quoted and considered in the text. All references are listed in chapter 11 of this report. Most of the references were published at CIRED between 2009 and 2019.

4.1 CIRED Papers

CIRED Papers were screened from 2007 till 2019 (covering six conferences). The authors of this report identified 122 papers related to the new roles of smart meters in grid planning and operation. Starting with a few contributions in 2007 and 2009, a significant increase (15 papers) even continued in 2019 (52 papers, see Figure 1).

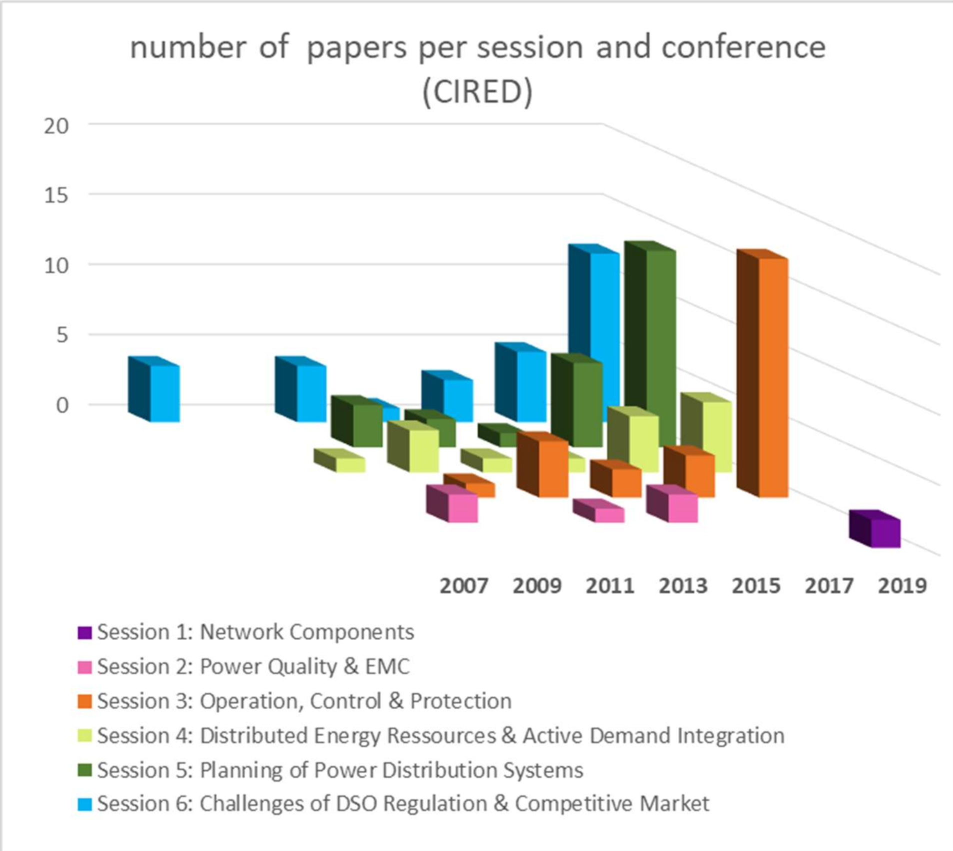


Figure 1: Number of papers regarding new roles of smart meters in grid planning and operation at CIRED

Figure 2 shows the origin of the papers published at CIRED. The leading countries in terms of number of published papers are Spain, Germany and Portugal.

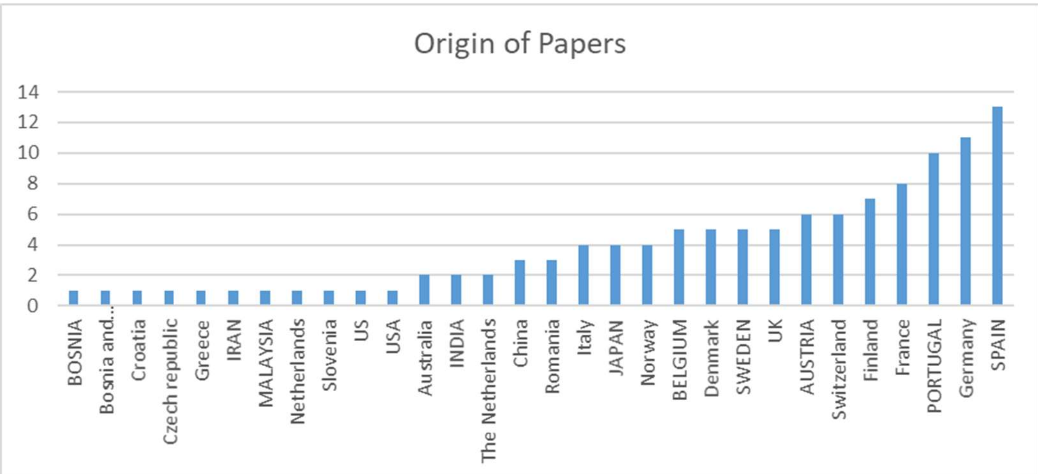


Figure 2: Origin of CIRED papers

Most of the papers refer to the grid management issues followed by planning and control. Some papers are allocated to more than one issue (see table 1).

Table 1: Allocation of CIRED papers to the use case classification of this report

Chapter	Title	Number of Papers
8.1	**Grid Management**	**66**
8.1.1	Monitoring LV Grid	21
8.1.2	Network Analysis - Topology assignment	9
8.1.3	Outages / Disturbances	13
8.1.4	State estimation	9
8.1.5	Customer monitoring	3
8.2	**Grid control**	**36**
8.2.1	Automation of LV Grid operation	19
8.2.2	Automation customer’s systems	14
8.3	**Distribution Planning**	**39**
8.3.1	Load Estimation for Planning	20
8.3.2	Revising design standard of distribution facilities	0
8.3.3	Grid ASSET PLANNING (Optimization of Life Cycle and capacity)	2
8.4	Not allocated	10

Around 10% of papers are related to more than one of the Chapters (8.1, 8.2 and 8.3). The number of papers in the sub-chapters is included. These are resulting in a total sum below as some papers could not be linked to any sub-chapter. In general, in most of the papers, details about parameters of the values used for control or planning are very limited. In many cases, just concepts or demonstration projects are roughly explained. The use cases presented in the papers are limited to the specific meter applied within the demo cases.

4.2 CIGRE Brochure

The starting point for the discussions within CIRED WG 2018-5 was the analysis of the CIGRE C6/D2 technical brochure on "Utilisation of Data from Smart Meter System". The report identified that data from the smart meter system has a big potential for providing valuable information for power grid management. The report provides an overview of the utilisation of data from smart meter systems, integrating and organising the values, tasks, and approaches to be taken, and making a proposal to the electric power utilities and associated market participants from a technological point of view. Besides the investigation of smart meter deployment status and smart meter functions worldwide, it includes the analysis of collected use cases. Each use case is categorised and analysed based on "which data is to be utilised?" and "who will utilise the data?". The use cases from the CIGRE brochure have been analysed as a starting point for discussing the DSO specific use cases presented in this report.

5 SMART METER AS AN INSTRUMENT?

Meters are compliant with requirements concerning measuring energy consumption (typically RMS 15 min average), usually as specified in the European Measuring Instruments Directive (MID) 2004/22/EC. Manufacturers have implemented different sensors and individual data acquisition algorithms regarding sampling, windowing, PLL (phase-locked loop) etc. It seems that enhanced functions are added retrospectively at every opportunity instead of being included in the initial design and development.

5.1 DATA GATHERING IN THE ELECTRICITY GRID – STATE OF THE ART

5.1.1 Instruments for operation – distribution management systems

For grid operation in all primary substations and selected secondary substations, simple analogue transducers (converters from AC voltage or current to RMS, often coded to 4-20 mA or 0-10 mA) are connected via RTUs (Remote Telemetry Units) to the DNO/DSO SCADA. The accuracy of this signal conversion is limited, and the transfer function is defined for the presentation of Data in SCADA systems. Standard SCADA communications protocols which began with periodic reporting have been improved over recent decades. So modern protocols (DNP3, others) include report by exception, triggered by a change of measured parameter. The integration interval for RMS detection is in the range of 0,2 seconds. From these data, 1 min, 15 min average values, maximum and minimum values are calculated. These data and load profiles from industrial customers (10 to 15 min profiles from metering) and synthetic profiles for small, often domestic, customers are used for network planning at LV and, through agregation and additional monitoring, at higher voltage levels.

5.1.2 Power Quality Instruments and monitoring

The design of electricity networks requires considering the given limits of rated currents, all PQ parameters and reliability. The European Standard EN 50160 provides typical maximum levels for relevant power quality parameters at low and medium voltage levels. PQ parameters and requirements for instruments are specified by international standards for assessment of power quality (e.g. EN 61000-4-7, EN 61000-4-15, EN 61000-4-30 etc.). EN 61000-4-30 provides detailed definitions for setting timeframes and synchronising the instruments' clocks. Most of the voltage quality parameters are defined for 10-minutes, calculated from 10/12 (50/60 Hz) periods values (e.g. voltage levels, harmonics, flicker) interval and for one period (voltage dip and surge). In the practice of power quality assessment, two different instruments compliant with the 61000-4-30 Class A requirements shall provide almost identical results. Power-quality instruments are typically installed for permanent use at primary substations. The total number of PQ monitoring instruments installed all over Europe, roughly estimated, is around 100,000. The price of such instruments is within the range of a few thousand Euros.

Further monitoring devices are installed at industrial sites and low voltage grids. This trend relates to the ongoing developments of power electronic devices, where closed monitoring is warranted at every single potential entry source (also referred to as a point of common coupling). An increasing share of distribution transformers is now equipped with grid meters. There are meters also covering PQ monitoring functionalities for capturing the upstream and downstream driven events. These functionalities are only within EN 61000-4-30 Class B requirements. Thus, the evidence of the results is limited to operational purposes.

Concerning PQ instruments' functionalities, there are many similarities to the next generation of smart meters. PQ monitoring is typically only installed at large industrial sites: in future this may be extended to all customers with such meters.

There is a large opportunity for complementary information that can be leveraged between smart meter and PQ meter to capture consumer-driven events and thus identify a violation of grid codes. Many academic research and proofs-of-concept have been carried out in different parts of the world to bridge the difference between smart meters and PQ monitoring instruments. [2] combined statistical analysis acquired from long-term data with real-time monitoring to propose an advanced metering infrastructure (AMI) in a larger framework. Such a system is called an integrated power quality monitoring system (IPQMS), as adopted by many utilities [3]-[5]. Smart monitored data from existing networks are utilised to develop a web services architecture for PQ monitoring [6].

Table 2: Measurement properties of most meters currently available

Type	Sample frequency	RMS-interval metering	RMS-interval to interface	RMS-interval voltage quality	Accuracy I, U, P, Q	Accuracy time	Accuracy energy
Covered by standard or regulation	No	Yes	No	No	No	Yes	Yes
Residential smart meter	Not defined but typ. 12.8 kHz	1sec / 0.2 sec (internal registers)	1s (limit here is usually the communication network is limiting)	100ms	No standard for residential only for energy	+/-0.5 sec/day	1…2% typ. 2%
Industrial smart meter and smart grid meter	Not defined	1sec / 0.1 sec (internal registers)	1s (usually the communication network is limiting)	100 ms	U,I: min: 0.5% P,Q: acc. Meter class:1% or better; IEC61000-4-30 Cl. S	+/-0.5 sec/day	Active 0,2…1% Reactive 0,5…2%

A typical approach is to get as much resolution as achievable, but it usually results in cost during the gathering, transmitting, storage, data management and post-processing. Therefore, the resolution should be reduced to the minimum requirement for the individual use case. Chapter 9 of this report (conclusions) provides a requirements table covering the use cases discussed in chapter 8.

6 DATA MANAGEMENT

Data acquisition is just the first and basic step of implementing smart grid solutions. Successful management of data means enabling access to all data in time and at the level of performance required by the use cases. All parameters should be defined in a standardised common information model (CIM) available from a certain number of meters on the market and supported by meter data management systems (MDM). [1] provides a detailed analysis of data management and utilisation of data.

7 COST BENEFIT ANALYSIS FOR IMPLEMENTING NEW ROLES

In the context of a cost benefit analysis (CBA) of smart meters related to use cases in power system planning, control, and operation, these business cases are generally in addition to the core benefits identified for any smart meter deployment.. In Europe, the original motivation for introducing smart meters was to save energy, and help avoid unforeseen debt through estimated metering readings, by letting consumers know their electricity consumption in higher resolution. In some countries, the main business case was even reducing non-technical losses (electricity theft). Additional use cases presented and discussed in the report have often not been considered nor included in any benefit-cost analysis.

The cost-benefit analysis considerations for implementing new roles must be performed in two steps so that the business-as-usual (non-smart meter) activity may be compared with the proposed smart meter solution. Costs should include the total cost for acquisition of data and interfaces for control independent from smart metering and the cost for processing data for simulations.

For DSOs, there are two fields of benefits in operation and grid development. For example, the French DSO Enedis identified a couple of benefits for MV and LV grid operation (see Figure 3).

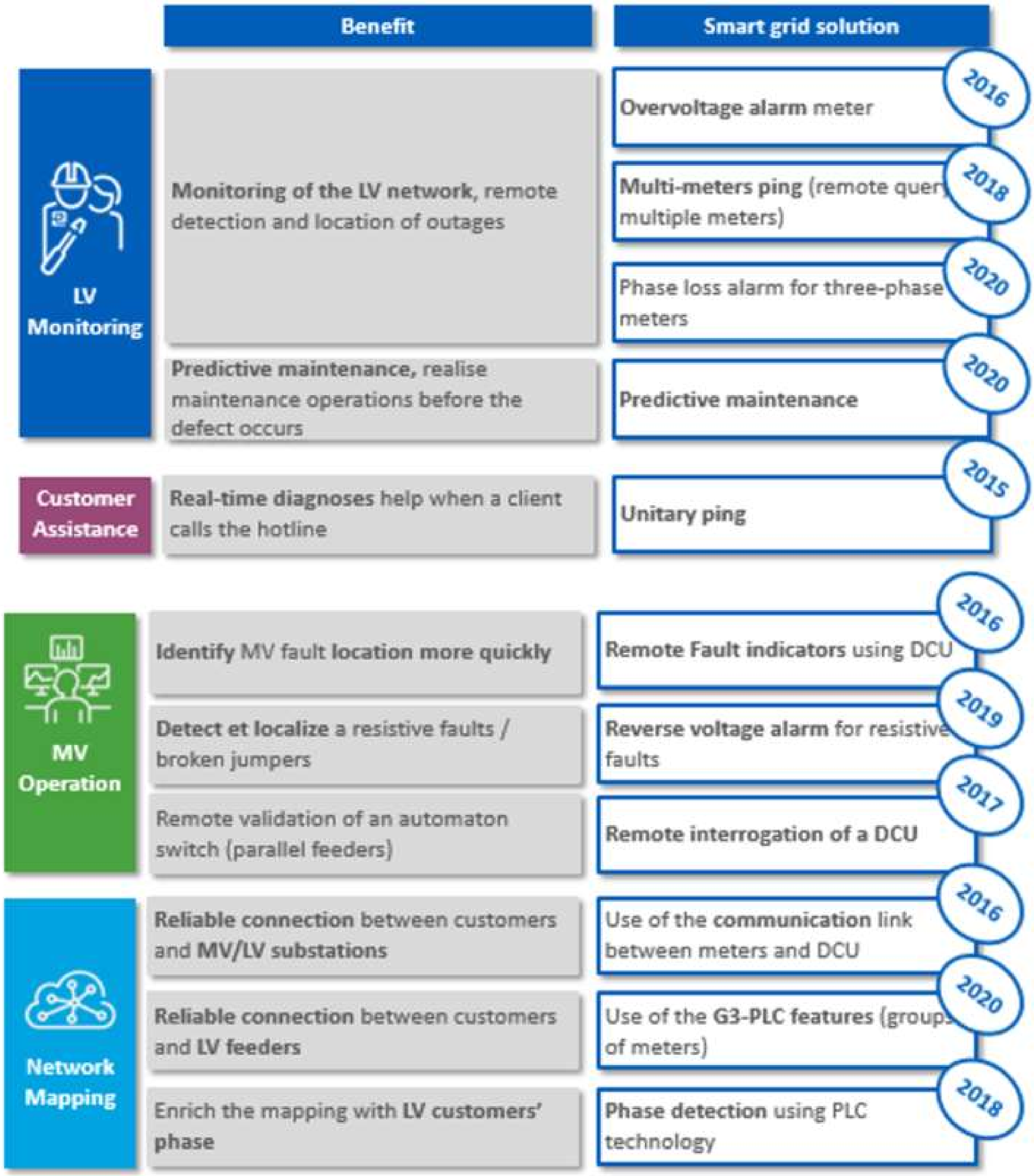


Figure 3: Benefits in operation identified by French DSO (Source, Enedis, France)

Further benefits often relate to the identification of hosting capacity for new generation and loads. The benefits or losses result from optimising investment to most relevant areas and activation of flexible loads to manage peak loading. As a second step, the CBA of implementing new roles compares the cost of implementing additional functions to the smart meters with the cost rising from installing independent solutions. If an implementation within smart metering systems results in significant savings, the impact on CBA of related use cases will provide better results.

In general, it isn't easy to provide concrete numbers concerning the benefit related to use cases in grid management, operation and planning since advanced methods based on wide-area data acquisition in MV and LV grids are not widely established yet. Many use cases have been regarded only including the implementation to smart meters. At the same time, the installation of independent sensors, actors, IEDs and communication for transfer was excluded due to very high cost. Many use cases seem to be of interest initially, but considering the costs and risks of malfunction or maintenance efforts, most of these ideas are not cost effective.

As significant parts of total costs of smart metering systems are almost independent of the number of customers for large DSOs, the CBA results are positive while small DSOs fail to benefit from this. Standardised solutions would fill this gap. A clear definition of use cases, standardised solutions for implementation and interfaces to data management systems might support positive CBAs for certain use cases besides metering of better quality in future.

8 USE CASES

8.1 GRID MANAGEMENT

The deployment of smart meter programmes is the first step towards more visibility of the LV grids. How the generated data can be implemented to manage LV grids more efficiently depends on the provided information and the communication technology. Various publications refer to the usability of smart meter data for Grid Management use cases; according to [7], the largest benefit of smart metering deployments is expected to be in Outage Management and restoration, whereas [8] already suggests a process to monitor PQ with the new generation of smart meters. Topology definition and feeder mapping are further use cases that can be supported by advanced metering infrastructure over power line communication (PLC), according to [9] and [10]. Recording the network state (from historic up to near real-time): by measuring the voltages and voltage angles at selected meters in the network (start, middle and end of a line/system), it is possible to determine and record the network state.

The management of the LV distribution grid requires monitoring network capacity limited by poor PQ, voltage levels, and load profiles.

8.1.1 Monitoring LV Grid

Voltage Monitoring

Increased distributed generation from variable renewable energy resources in the LV grid leads to voltage variations that depend on the consumption and generation profiles. According to EN 50160, DSOs usually define the voltage range in the LV grid between -10% and +10% of the nominal voltage. Due to the dynamic profiles of modern grid users (charging stations, distributed generation), these voltage levels cannot be predicted as easily as before. Smart meters provide voltage measurements in separate registers and generate events indicating voltage violations in real-time. Depending on the communication technology in place, various methods, like the "Synchro-SCADA observability method" proposed in [11], can be applied to enable more real-time voltage monitoring.

Capacity Monitoring

In many countries, globally, grid capacity in the LV network is not yet an issue. However, local line or transformer over-loadings may occur – especially when connecting large distribution generation units in rural areas. Smart meter devices provide current information, enabling DSOs to calculate the grid loading in % of rated current in minute integrals. By monitoring grid hosting capacity, DSOs can better understand the utilisation of their network and plan investment decisions accordingly. With the measured values moving from average values of P, Q and V towards minute intervals of several households and energy generating systems connected to a line, the trend of the grid utilisation can be determined, and strategies can be derived accordingly.

The use of load profile data from smart meters in European countries depends on European directives implemented in national laws. Since, in some cases, legal privacy frameworks require the customers' agreement, the load has still to be estimated for a certain part of customers.

Power Quality

PQ is expected to be impacted by the increased number of power electronics connected to the LV grid. Today's state-of-the art DSOs is the sporadic measurement of PQ indices using mobile devices. However, without appropriate continuous measurements, it is impossible to know the impact of such new connections on supply quality. Smart meters, being the key sensors in the LV grid, can provide part of PQ information, contributing to a significant degree towards the monitoring of PQ throughout the whole LV grid area, as also suggested by [12]. While industrial meters and advanced PQ devices can already deliver PQ data according to EN 50160, new generation smart meters connecting households and small PV solar panels can deliver information about slow changes of voltage amplitude and events signalising faults. Such information can contribute to a detailed PQ supervision and fault detection system.

8.1.2 Network Analysis - Topology assignment

Synchronous distributed measurements are planned using the power snapshot analysis method that helps realistic grid model planning and accounting for the uncertainties arising in a weak grid [13]. Such models can help simulate futuristic scenarios of high PV or EV loading penetrations. Italian distribution operator ENEL leveraged STami, an AMI infrastructure that bridges MV and LV network monitoring with the help of smart meter data [14]. The paper discusses the potential of using all these data from the smart meter for smart network analysis, enabling automatic fault clearance procedures and helping in LV network monitoring, management, fraud detection in the network, etc.

Automatic phase identification is proposed in [15] from the smart meter data in an LV network. This helps DSOs detect voltage unbalances and define subsequent remedial action by phase change actions in both loads and PV integration frameworks. It uses graph theory and a maximum spanning tree to maximise the correlation between the voltages of the nodes. The phase connection order of all smart meters supplied by the same transformer is detected accurately up to 82%, using 15 minutes sample of AMI data sample in the E-on distribuce in the Czech Republic [16]. Enedis and EDF take advantage of a PLC network for the local phase detection in the AMI of the LV network [17].

Five minutes snapshot of voltage and current data from smart meters is utilised in the advanced data analytics context to gain detailed LV network visibility in the state of Victoria in Australia. The benefits of LV grid supervision are highlighted in [18]. With the advent of AMI in the LV network, secondary benefits such as demand response management, load balancing, renewable integration, etc., from the LV grid monitoring perspective become apparent.

8.1.3 Outages / Disturbances

This section distinguishes between different network states and how smart meter data can help prevent and overcome such states.

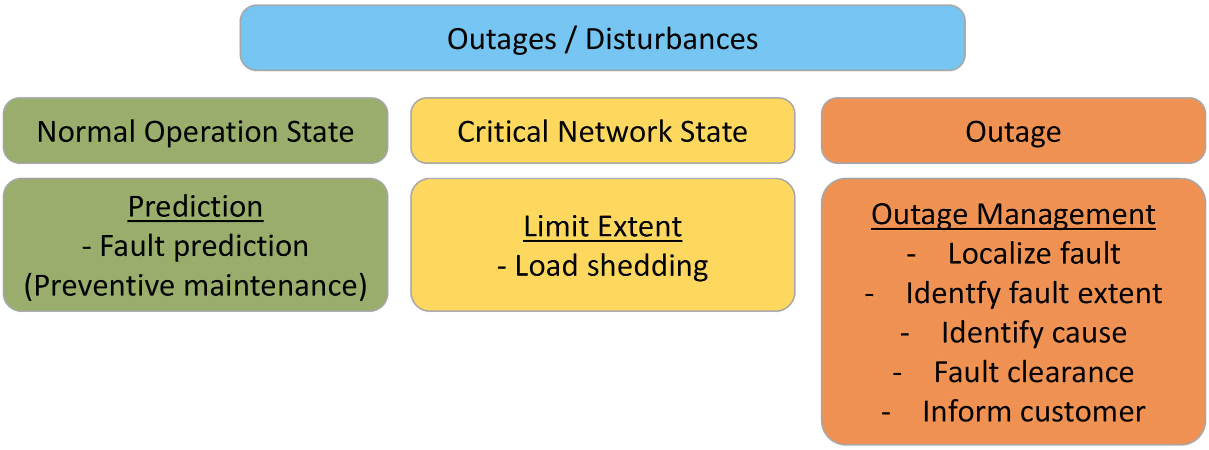


Figure 4: Prevention and management of outages and disturbances at different network states

Data from different network states must be considered in the grid planning process (see Section 8.3 Grid ASSET PLANNING).

Normal Operation State
In the green "Normal operation state", no critical network situations exist. The network operator observes the network status. To prevent outages due to faults of network components, fault prediction and preventive maintenance can be implemented.

Critical Network state
In the amber "Critical network state", there exists potential or actual network congestion and the risk of outages. The network operator remedies the situation by utilising the flexibility offered by market participants.

Outage
In the red phase, "Outage", the network operator must manage the outage or disturbance.

In the case of a power outage or a disturbance the

- Time
- Duration
- Extent (outage area, energy not delivered, power not provided) and
- Cause (Short circuit (force majeure), overvoltage, …)

of interruptions must be recorded and submitted to the regulator (e.g. relevant for quality element in the German incentive regulation equation[1]). Smart meter data support reduces outage duration and costs since the outage causes can be quickly located and repaired. With smart meter data, problems often caused by severe weather events can also be identified.

Detection of broken wires in the distribution system: e.g. open circuit and high impedance faults (HIF) involving uprooted trees leading to very low or no fault current, thus not triggering the relay protection. These faults often go undetected when the phase conductors are unbroken. AMIs installed on the LV side of secondary substations can help detect the HIF by including LV supervision devices [19] that detects voltage unbalances. Iberdrola has tested this detection passed via AMI as events into the Energy Management/SCADA control systems.

[1] ARegV - German directive on incentive regulation for energy supply grids (in German)

Simultaneous measurements of AMI parameters were obtained in different network nodes within the permissible timeframe that the infrastructure supports. The results are extrapolated for a longer period to form a basis of distortion calculations in 110–kV- and 20-kV-network in the Romanian grid [20]. This gives a reasonable PQ estimation of the network. Integration of AMI data with the DMS/ SCADA system would offer higher reliability of communicating the interruption and outages both upstream and downstream, in addition to detecting actual incidents [21][22]. This is just a concept presented in a paper by Vattenfall. However, [23][24] implemented this concept using 1st generation smart meter in Sweden. The latter paper aimed to capture and localise outage and interruption events with extensive data gathering to feed to the 2nd generation automated meter reading (AMR) smart meter enrollment.

Outage management system (OMS)

Providing timely and accurate information about outages and restoration is a critical opportunity. Customers expect utilities to:

- Know that the power is out, even if no one is home to call
- Tell them when power will be restored, and provide updates on the progress
- Provide two-way communications options according to personal preference

Smart meter information can be provided to customer service systems to proactively inform customers about their outage, such as, "We know there is an outage in your area. The estimated restore time is….". Customer service representatives can also be given the ability to 'ping' a customer meter while the customer is on the phone to identify if the outage is on the customer or the utility side of the meter.

Disconnecting selected customers, or loads, during network overload situations can help to avoid overloading the electricity distribution lines, especially during change of frequency (RoCoF) circumstances, which can lead to blackouts if unchecked. Disconnection of customers/loads to mitigate a low or high frequency situation need to be remotely configured within the smart metering system software, and a different frequency value can be set for each customer. This action might enable differentiated and graduated load shedding for more balanced load management, and the DSOs may avoid, or reduce the extent of, blackouts as has been common practice until today. The DSO can also predefine the reconnection of each customer. When the peak load crisis is over, customers will be gradually reconnected to the grid. The switching functionality of the smart meters can help the DSOs to perform gradual and selective load shedding on the customer level without disconnecting all customers within a substation area. Preselection of load shedding needs to be made so that prioritised customers such as clinics, pharmacies and the elderly/vulnerable will not be limited or disconnected [25].

[26] outlines the advantage of the new generation smart meter rollout in Norway in 2019, helping to improve fault detectability, especially in rural grids with a low density of customers. This is based on voltage quality monitoring of the meters, statistical data collection over PQ indicators and effective customer complaint handling, etc. The French DSO Enedis undertook a massive rollout of an advanced meter management system with 300,000 meters to prepare a pilot technical architecture that helps to improve the fault location and supply restoration [27]. The paper presented the communication infrastructure development and the evolution of the AMI in various phases. A smart meter network's systematic data collection and application integration are proposed for the Chinese Southern Power Grid (CSG) for precise and fast fault location in the LV consumer network [28].

An architectural backbone in the LV network in a Spanish demonstrator is created that consists of Smart meters DSO meter data management system (MDMS). It is similar to an MV SCADA. The network of smart meter aggregates ½ Million smart meter data in the MDMS which identifies 700,000 events. The paper paves the way for large-scale data analytics from Smart meters, helping the LV network operations in a very detailed way [29]. EdP España, Spain [30], have carried out a similar exercise. The smart meters do not register the variables in the internal memory but send the voltage quality events upwards in the network for a common aggregation. The equivalent of 650,000 smart meters sends 300-400 events per minute and 100 quality events per minute. An artificial intelligence (A.I.) based automatic learning system groups and orders the over and undervoltage events for the benefit of the network operator. This helps addressing the grid failure with appropriate urgency. The use of machine learning (ML) techniques for operational support systems has been exhibited [31]. This paper uses smart meter data together with weather data. It uses a case-based reasoning method to assist in the decision-making of daily operations and future fault handling of the LV distribution network.

Oncor, the largest energy provider in Texas, combined AMI data with OMS and sent out 1400 notifications to the system operators within the first six weeks of this integration. Half of these notifications were linked to actual outages, rectified before the customer complaints were registered. A significant part of these alerts could also be attributed to power quality issues, such as open neutrals or bad connections, those the utilities managed to address proactively [32]. Similarly, CGI reported an OMS to use a case in Italy based on the last gasp principle to analyse a real-time situational view, thus helping to isolate outages from the smart meter pings [33].

A further option is not to disconnect meters during network overload situations but to limit consumption, enabling light and communication strongly.

8.1.4 State estimation

State estimation supported by smart meter data can contribute to several use cases by providing or compensating missing data or supporting different forecasting approaches for predictive management and control. Related to low voltage grid state estimation, two central topics are discussed: First, comparing different state estimation methods like the conventional method or linearised methods and second, the consideration of privacy issues. The results show that the conventional state estimation is the best option if the process cycle of a supervision system is long enough [34]. Meter placement for low voltage system state estimation, through deciding which measurement data from the installed smart meters, should be considered in the state estimation algorithms to improve the uncertainty of the estimated voltage and its phase angle at every node in the network [35]. The "Monica" Project on monitoring and controlling distribution networks introduces a combination of sensors and smart meter data for analysing LV grids, even applying real-time state estimation and alarms to avoid incidents [36]. The "Integrid" project has developed active management of low voltage grids. Smart meter data from the past is used for real-time state estimation by matching monitoring data with recent observations. The voltage control can be optimised based on the state estimation's results and P.V. forecast [37]. In general, if distribution system state estimation lacks real-time measurement data, missing measurements can be compensated by using historical data, so-called pseudo-measurements. The use of these measurements, meta information, e.g. time of day, and probabilistic estimation methods of active power sum are essential for real-time application and might further reduce the estimation errors [35]. Several distribution management systems for active management of LV grids apply data management and processing to compensate missing data and for predictive maintenance, state estimation and phase identification. To do so, smart meter data can be used together with SCADA data [38].

8.1.5 Customer monitoring

Data about consumption behaviour supports DSOs and retailers to improve load models of their customers. Analysing customers according to their consumption similarity will assist DSOs and retailers in designing electricity rates that can facilitate demand response applications. But maybe this is resolved with a flexible market where qualified customers and retailers as aggregators offer flexibility to DSOs and transmission system operators (TSOs).

Before implementing smart metering, it was impossible to accurately identify real-time consumption patterns of customers on a large scale. In [39], a data mining technique based on Self-Organizing Map (SOM) to group customers according to their actual consumption is presented. A SOM is an artificial neural network (ANN) as a 2D representation of a multidimensional dataset. It is used to get insights into the topological properties of input data to determine clusters. In this specific case [39], the following variables were used: Consumption (kWh), Peak Load Value (kW), Tariff Code (comprising five categories: normal rate, economic rate, time rate, irrigation rate and temporary working rate) and Housing type (also five categories: summer cottage, detached house, in a townhouse, multi-storeyed building and others). Interesting results were obtained, such as discovering that customers with high consumption profiles chose the normal rate instead of other rates which should favour them. So, a SOM-based customer consumption behaviour profiling method can provide added value to some customers.

Consumption patterns and other characteristics from smart meters can also be used to pre-select suspected customers to be inspected on-site for abnormalities, billing errors or potential fraud [40]. [40] presents a hybrid method using algorithms such as Support Vector Machine (SVM) and Modified Genetic Algorithm (MGA). For the validation of this algorithm, monthly readings from 3 to 6 years were used, and the accuracy was 94%.

Recently EVs have become an increasingly important issue in the sustainable supply network, along with distributed generation, PV and inverters or new heating systems, and undoubtedly these new systems affect consumption patterns.

The number of EV charging stations is steadily increasing. As a result, EV charging stations can be found in private residences, public dedicated stations, and commercial and residential buildings. For residential use, this new element will affect the consumption pattern, and it is time to analyse this to understand the effect EVs will have on the grid. Still, it is important also to consider the impact of public charging stations, and in these cases, a smart charging infrastructure based on smart metering solutions may be of benefit.

On the other hand, more and more households are opting to install PV modules driven by the lower investment costs. With this transformation, household consumers are becoming active prosumers.

Customers require more features than provided by smart meters to meet the real-time requirements for automation an presentation via monitoring platforms (PV installations, heating, etc). Some these informations obtained separately or segregated by different measurements elements would add great value to the DSO for analysing consumption patterns and behaviour at the household level and the individual device level within the household.

8.2 GRID CONTROL

8.2.1 Automation of LV Grid operation

Automation of an LV grid mainly involves switching in case of disturbances or planned maintenance work. It depends on the topology and density of loads/customers and options to vary the topology by interconnecting neighboured LV grids to maintain or optimise the power flow.

Manual operation of LV grids cannot be applied for optimising the topology depending on seasons, weekdays or even the weather. Therefore automation would be required, but usually, motor-driven switches with interfaces to IEDs are currently not installed to the LV grid.

Voltage control and demand control require automation in LV grids. Local autonomous controllers shall be supervised and support a remote setting of parameters (e.g. setpoint) remotely. The role of the smart meters for controlling is "sensor" measuring load/generation and voltage levels. The setting is based on load data, voltage levels or state estimation from meter data.

Requirements for monitoring in LV grids are quite different from those for medium or high voltage systems, focusing on supervision of loading, voltage levels and performance of autonomous controllers and any other high value network assets.

At CIRED 2019 a few papers [37], [38], [41], [42], [43] reported the use of smart meters within Portuguese demonstration projects. In most cases, the smart meters deliver data to an enhanced solution with additional IEDs implemented to SCADA. Typically, smart meter data from past periods is used for state estimation, supporting an optimised voltage control in one case [43], the smart meter interfaces with the customers. Customers were also linked to the market. This project's heating, PV installations and batteries were integrated regarding use cases up to islanding with balancing the microgrid. [44] reports about a grid control demonstration project in Germany where inverters and intraday load control is managed. Following a traffic light approach, the DSO requests reactions from customers with their flexibilities by quotas that could even be traded. The smart metering communication protocol used Modbus. In a Japanese project, smart meters are successfully used for optimising the voltage control in LV grids [45]) and balancing demand/supply based on wide-area real-time data from smart meters [46]. [47] presents a digital twin built from topology data, line sensors and smart meter data for optimised operation, in fact, a model (TWIN) and state estimation and optimisation of voltage controller based on near real-time data. In a U.K. demonstration, voltage level monitoring from smart meters is proposed for automatic reconfiguration of LV grids with remote-controlled switches [48]. However, the paper also states: *„smart meter installation in the UK, as of 2018, is voluntary. As a result, some parts on the circuit will not be monitored and there will be no data to create the model for that customer."* [49] reports about the integration of smart meter data into the IT-systems of SCADA of a newly installed Distribution Management System based on CIM (Common Information Model). From Switzerland [50] reports about the project "Quartierstrom" with a local energy community where IEDs (low-cost Raspberry Pi devices) with metering functions were applied. The system with market functions also includes the DSO as a partner with the interest of voltage supporting demand management is operated with 30s cycle. Compared with the 10…15 min metering intervals used for billing this causes up to 30 times more meter data traffic. The projects indicate that today's smart meters, especially their communication systems, are not ready to support such use cases.

8.2.2 Automation customer's systems

Smart meters have significant potential to improve the service levels provided to prepaid consumers. They also open new tariffs and demand-response or flexibility products to help manage grid constraints and renewables integration.

AMI, combined with other technologies such as in-home display, enables utilities to offer new time-based rate programs and incentives to encourage customers to reduce peak demand and manage energy consumption and costs. Real-time data for consumer-focused applications results in substantial savings. Consumers gain a better insight into their energy consumption, resulting in more rational electricity use in most cases.

The technology for metering is relatively mature. However, key challenges remain around the communication interfaces, not only with the utility but also with the HAN. The paper [51] proposes an energy meter using the MQTT protocol through an internet-based connection to an MQTT broker from which data is forwarded to the central system. This provides a two-way communication channel, enabling load control at the household level.

By using Smart Meters, the DSO can manage the demand side during peak load crisis and decrease the risk of blackouts. The smart meters may allow the DSOs to switch loads in an area, but this might impact the Power Quality of the grid. This has been described in the paper [34], where a gradual increment or decrement of loads is proposed instead of a sudden big change in the grid.

Demand-side management projects [10] demonstrated that AMI and customer systems could achieve substantial grid impacts and benefits for customers and utilities, including:

- Reduced costs for metering and billing
- More customer control over electricity consumption, costs, and bills thanks to new customer tools and techniques.
- Lower utility capital expenditures and customer bill savings resulting from reduced peak demand.
- Lower outage costs and fewer inconveniences for customers from faster outage restoration.

Consumers need to be engaged in the benefits of smart metering to be proactive in saving money.

Smart meters can facilitate demand-side response (DSR) through different load control features (load control services, time of use tariffs or power-based tariffs [52]). [53] explains how the G.B. smart metering system can support different load control mechanisms to make domestic demand-side response possible, including new products and services: demand aggregators, smart appliances or Home Energy Management services. There are similar experiences in other countries, providing home area network (HAN) devices integrated with consumers' smart meters, enabling them to manage their usage, determine the energy usage of home appliances, adjust temperature settings according to price signals and make smarter energy decisions to reduce overall usage and costs.

Time of Use tariffs is the key to obtaining the benefits of DSR as they can give consumers a direct financial benefit from shifting when they consume energy. A time-of-use tariff offers a different energy price at different times of the day. Such a tariff may be a static scheme (e.g.

prices vary according to calendar) or dynamic (prices vary according to ad hoc signals sent by energy suppliers).

8.3 DISTRIBUTION PLANNING

Electric distribution system planning supports investment decisions and operations strategies. It is a broad subject with many facets. The increasing number of distributed energy resources (DERs) and smart meters connected to the grid is changing how utilities perform their distribution planning process.

The network operators' fundamental goal is to better utilize the existing networks or the further integration of decentralised generation plants and additional loads with the lowest possible network expansion. Various new concepts are being developed and examined to achieve these goals. They range from increased ICT and intelligent secondary technology to new components, e.g. controllable local network transformer or reactive power control.

The data provided by smart meters allow new network analysis methods for low-voltage networks. Precise voltage and power measurement data in the four-wire system enable improved use of low-voltage networks for consumers and easier integration of decentralised generation systems and e-mobility. In addition to measuring consumption data, the intelligent meters are also assigned the task of remote control of loads and generating systems [54]. In other studies, intelligent meters for network planning and operation are not required at every network connection point. The cost/effort associated with the deployment of smart meters and the necessary communication infrastructure is considered disproportionately high compared to the benefit from load shifting [55], [56]. Instead, measurement data at critical points in the network are used to estimate the state, enabling a precise overview of the network situation [35].

The flow diagram of distribution network planning in the context of the energy transition is illustrated in **Erreur ! Source du renvoi introuvable.**. The left column lists aspects that are of relevance in the distribution grid, while the right column lists aspects that are more relevant at the customer connection point. The functions shown in green may be improved through the deployment of smart meters.

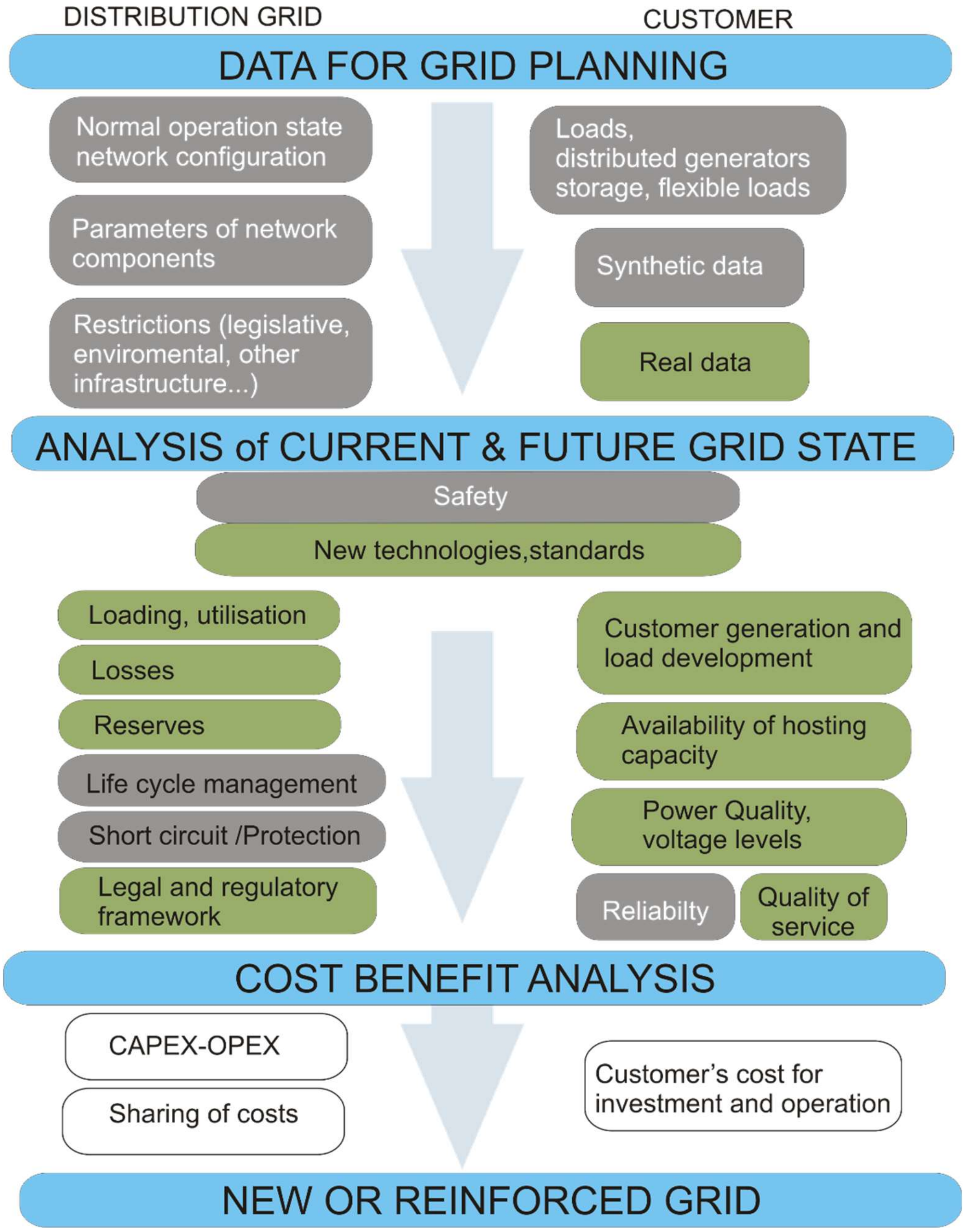


Figure 5: Flow diagram of the technical aspects of the distribution system planning

8.3.1 Grid planning based on real data

Load Profiles

Future customer loads and feed-in forecasts are fundamental to distribution system planning and necessary to evaluate future system constraints and investment alternatives.

Customers connected to medium voltage networks usually have a load profile measurement, which means the data relevant for power flow calculation is available.

If a low voltage network needs to be reinforced, the network is often assessed using peak load and generation values. These values used to be estimated based on the annual energy consumption of typical low voltage customers since measurement data are only available to a limited extent [57]. Another limitation of the presently used approach is that it does not easily allow for information available to DSOs about customers on a specific feeder to be incorporated into demand models.

With the introduction of smart meters, measurement data from users and, in special cases, also of each phase of the line become available for the DSO. A more realistic worst-case scenario can be used for power flow calculation.

With improved network calculations, peak loading, which is the most important planning criterion, can be estimated more accurately at each point of the LV network. In practice, this means that the dimensioning of MV/LV network components (e.g. OLTC), Q(U) voltage control and protection units can be optimised [58]. In addition, the losses can be evaluated more precisely, and trends in peak loading can be indicated [59], [60]. AMM deployments also allow identifying unbalanced LV networks and considering the possibility of large-scale balancing plans [61].

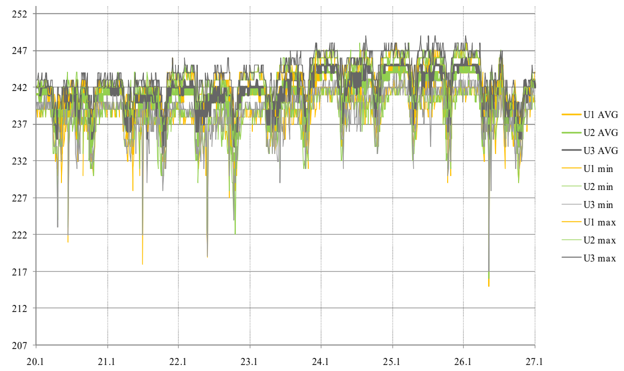
However, the use of the smart meter data also raises questions:

- Sampling frequency: In [57], it is shown that measuring at slightly lower sampling frequencies (from 15 min onwards) still allows a reasonable estimation of the peak load compared with higher sampling frequencies.
- Measurement duration: It has been shown that the peak load can be estimated with an accuracy of over 90% on one month of measurements a year [57].
- Percentage of measured customer or used meter data: [62] found that 50% Smart Meter coverage brings the optimal accuracy for overall (active and reactive) load decomposition compared to the base cases.
- Individual load curve vs larger groups of customers.

Due to the huge amount of data generated by smart meters, methods of machine learning, big data analysis and statistical methods such as Monte Carlo Simulations are used more and more [63], [64], [65], [66].

Voltage Levels

In rural areas, the planning of medium and low voltage grids focuses on voltage rise and drop. In existing grids, assessing customers' requests for connection of decentralised generation or load requires an estimation of loads and generation to calculate voltage levels. Real voltage levels from wide-area measurements and voltage rise and drop caused by the requested connection can be used for a more realistic modelling in planning low voltage grids. At CIRED 2009, the Austrian DSO NetzOOe presented a concept of a related use case for monitoring voltage levels with smart meters [67]. Instead of profiles, simple statistics are provided for each week by counting classifications of 15-min-voltage level values (minimum, average and maximum values) to 11 registers in each meter.



Class	Voltage Range
Class 11	U > 111%UN
Class 10	111%UN >= U > 109%UN
Class 9	109%UN >= U > 107%UN
Class 8	107%UN >= U > 105%UN
Class 7	105%UN >= U > 103%UN
Class 6	103%UN >= U > 97%UN
Class 5	97%UN >= U > 95%UN
Class 4	95%UN >= U > 93%UN
Class 3	93%UN >= U > 91%UN
Class 2	91%UN >= U > 89%UN
Class 1	89%UN >= U

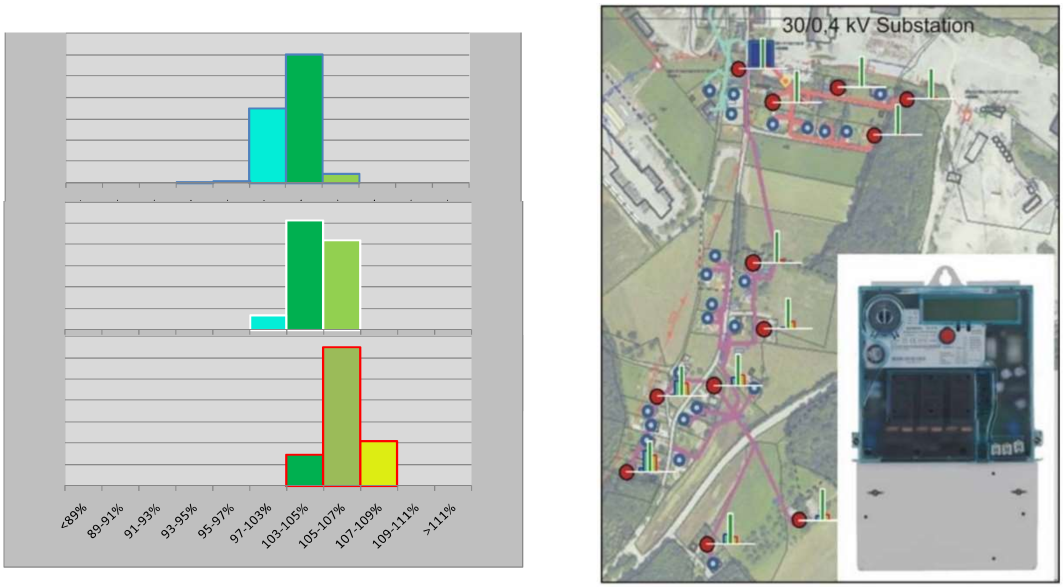


Figure 6: from timelines of voltage levels to roughly classified histograms

Figure 6 shows a one-week timeline of voltage levels at one customer site resulting in the histograms for minimum, average and maximum levels. An example for one LV feeder shows the meter and selected customer sites with small histograms for voltage levels for one week.

After 11 years at this Austrian DSO, the deployment of smart meters has reached a level of 99,5 %. The voltage level statistics function described above, called "voltage guard", is available for 95% of low voltage grids.

Figure 7 shows the presentation of results in a geographical information system (GIS). On top of the figure, all meters are presented as coloured dots. The colouring indicates voltage levels of the previous week. Other criteria for colouring the dots are under development. The historical histogram data can be indicated as carpet plots for each dot.

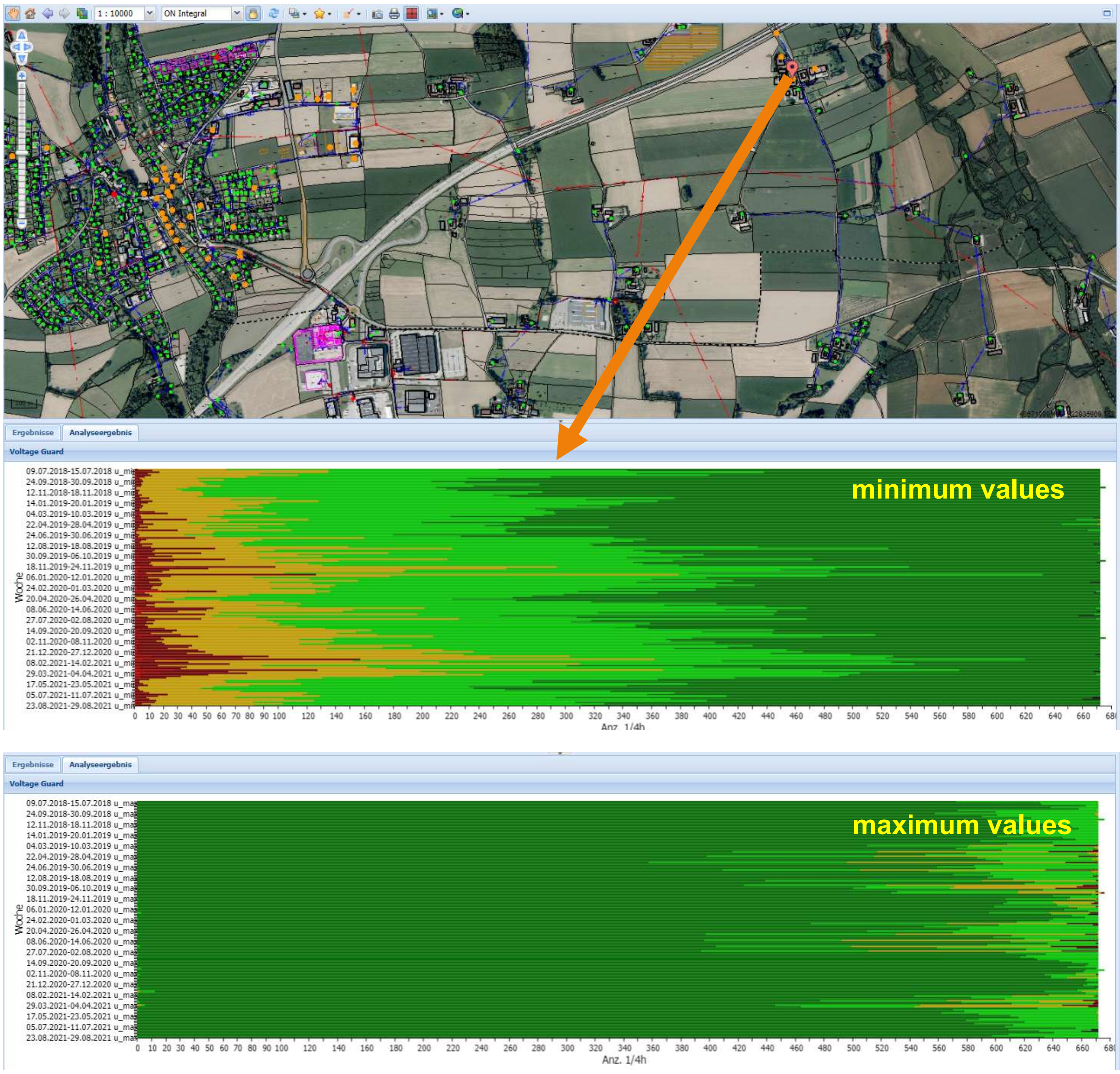


Figure 7: Screenshot of GIS application for "Voltage Guard" – data presentation

The data is used to assess connection requests, revise the loading modelling, and analyse available hosting capacities for expected requests for a decentralised generation. The data is used for prognosis and grid reinforcement for efficient asset management.

8.3.2 Revising design standards and strategies of distribution facilities

Every system operator has developed its standards based on topological (rural and urban), geographical and demographic conditions and considers how the existing infrastructure evolved and developed in the past. Thus, there are rarely common standards shared by different system operators.

Considering current methods for MV or LV grid planning, use of detailed data, as provided by smart meters and other sensors, is a challenging task in respect to currently available grid planning tools. In the last 15 years technical concepts and solutions for increasing the hosting capacity in voltage controlling and demand-side management have been developed. To investigate them as an alternative to traditional grid reinforcement, there is an urgent need to define simple criteria to check the quality and impact of different solutions and finally identify the best option. To do so, methods and tools are needed to:

- define technology rollout scenarios to be considered in grid planning (e.g. PV, EV, heating, cooling)
- specify and model different measures for reinforcing grid infrastructure, including the consideration of different flexibility options
- define and describe calculation approaches to evaluate the grid reinforcement needs based on defined future scenarios
- assess the impact of the different measures and their combination by comprehensive grid simulations.

These methods would enable a quantitative assessment of the impact of medium to long-term technology options on the entire supply area hence the revision of design standards and strategies of distribution facilities. Smart meters are suitable to regularly provide load data to be considered and integrated into enhanced grid planning tools to evaluate past planning and design standards.

For operating a large number of different technologies and flexibilities, like voltage controllers and demand response schemes, automated management and a verification system are needed - especially for devices that are part of a system installed at customers. In such cases, smart meters could be implemented as a simple and robust interface to customers' equipment and a surveillance (monitoring) module. An international standard could be established to define common requirements for smart meters.

8.3.3 Grid asset planning (Optimisation of life cycle and capacity)

Beside risk management, the ultimate objective of asset management is to help reduce/minimise/asset lifecycle costs across all phases, from asset investment planning, network design, procurement, installation and commissioning, operation and maintenance through decommissioning and disposal/replacement. Optimising the costs associated with each of these lifecycle phases remains among the key objectives of an asset-intensive utility organisation.

These challenges have forced utilities to leverage analytics to extend the life of assets and bring more predictability to their performance and health, which ultimately helps them plan and maintain activities.

Predictive analytics uses statistical and data mining techniques to analyse historic and current data sets, create rules and predictive models and predict future events.

Up to now, there are only a few installed measuring devices in the distribution grid. Still, many data like distribution transformer loading, load factor, voltage unbalance factor, harmonics, overload due to short circuit currents, etc., can be used [68].

[69] presents a new calculation tool for LV networks design based on AMM data, individual load curves and real phase connections. This tool was implemented in DIgSILENT PowerFactory and linked to GIS and AMM systems to perform automated server calculations. The project demonstrated improvements in LV network optimisation, including phase load balancing.

9 CONCLUSIONS AND OUTLOOK

Several activities and practical implementations proved that smart meters and related infrastructure can support the management, control, and planning of distribution grids. In addition, smart meter data can provide complementary information to PQ monitoring. An important issue is that regarding benefits from additional functionalities, a CBA is difficult to be made as to the reference costs for a system without metering are not available. For some of the use cases, the calculations of the benefits require assumptions as there is a lack of experience.

The working group identified the following promising specific objectives and related use cases along with the three DSO tasks; management, control and planning of grids:

Grid management

The main benefit of using smart meter data is to increase the visibility of LV grids. It includes the monitoring of voltage, grid capacity and power quality. The specific use cases include:

- Network state Analysis & Topology assignment
- Outages / Disturbances detection and prevention
- State estimation
- Costumer monitoring.

Grid control

DSOs can benefit from smart meter data and related communication infrastructure supporting the automation of LV grid operation. It includes switching, maintenance but also the remote setting of distributed controllers. This can enable new services at the customer level, like demand-side management. The two specific use cases identified are:

- Automation of LV grid operation
- Automation of customer's systems

Distribution planning

The main objective is to utilise existing networks better and further integrate decentralised generation plants and additional loads with the lowest possible network expansion. Data provided by smart meters allow new network analysis methods for LV networks. The specific use cases are:

- Grid planning based on real data (load profiles and voltage levels)
- Revising design standards and strategies of distribution facilities
- Grid asset planning (optimisation of life cycle and capacity).

The presented use cases are part of the solutions to the electricity sector. The individual use cases are driven by circumstances like decarbonisation goals and the technical developments in data analytics and information technologies. The latter results in a challenge for standardisation since interoperability across manufacturers, different generations of meters and communication technologies is requested. In addition, it requires an integration of smart meter data in other DSO IT infrastructure (related to management, operation and planning). In the course of smart meter rollouts, many distribution system operators are still challenged by integrating the meters and the related meter data management systems in existing IT systems to enable billing. Additional issues are involved in the integration of smart meter data with network management, operation and planning IT systems. Network related tools are often integrated into individual, highly secure IT systems.

Installing smart meters results in a more or less accurate real-time information instrument for new use cases for each customer. During smart meter deployment planning, many use cases initially seem to be of interest. Still, these ideas become less cost effective after considering costs and risks of malfunction or maintenance efforts.

Implementing specific functionalities to smart meters for domestic customers is limited for small and medium DSO (number of customers < 5 Million). Due to the small number of meters, this option is probably too expensive. Thus, only standard functionalities available on the smart meter market can be applied.

The working group discussed the properties of measured parameters for the use cases reported above, which resulted in table 3.

Table 3 Recommended standards for properties of measured parameters for different use cases

		W		**P**		**Q**		**U**		**I**		
		kWh	kVarh	kW		kVar		V		A		
8	Use Cases	acc.	acc.	int	acc.	int	acc.	int	acc.	int	acc.	remarks
8.1	**Grid Management**											
8.1.1	Monitoring LV Grid	2%	2%	5 min	2%	5 min	2%	5 min	2%	5 min	2%	*statistics or profiles*
8.1.2	Network Analysis - Topology assignment			1s	2%	1s	2%	1s	2%	1s	2%	*short sequences*
8.1.3	Outages / Disturbances			push/ instant	2%	push/ instant	2%	push/ instant	2%			
8.1.4	State estimation	2%	2%	5 min	2%	5 min	2%	5 min	2%	5 min	2%	
8.1.5	Customer monitoring	2%	2%	5 min	2%	5 min	2%	5 min	2%	5 min	2%	
8.2	**Grid control**											
8.2.1	Automation of LV Grid operation			push/ instant	2%	push/ instant	2%	push/ instant	2%			
8.2.2	Automation customer’s systems			push/ instant	2%	push/ instant	2%	push/ instant	2%			
8.3	**Distribution Planning**											
8.3.1	Load Estimation for Planning	2%	2%	15 min	2%	15 min	2%	15 min	2%	15 min	2%	
8.3.2	Revising design standard of distribution facilities	2%	2%	15 min	2%	15 min	2%	15 min	2%	15 min	2%	
8.3.3	Grid ASSET PLANNING (Optimization of Life Cycle and capacity)	2%	2%	15 min	2%	15 min	2%	15 min	2%	15 min	2%	

AMI deployments highlight several continuing challenges for grid modernisation that the industry should address [70]:

- Advanced data analytics could help utilities extract additional benefits from AMI's large volume or interval load data.
- Consistent data formats and more comprehensive interoperability standards are needed to achieve optimal levels of interoperability for smart meters, customer devices, and communication and information systems.

Related to the cost-benefit of using smart meters for management, control and planning, contradictory demands need to be considered:

- Provide related data for billing with minimum costs to fulfil what is required in directives related to smart meter rollout. Fulfil minimum requirements as cost-efficient as possible.
- Provide additional data for use cases that are not requested for billing purposes. The cost-benefit for these additional services is still very difficult to calculate.

The overall role of smart meters related to the use cases described in the report is to act as a source of selected and processed data to support grid management, operation and planning. Due to data privacy and protection requirements the usage of AMI data is limited and, therefore, investments in IEDs and operational measurement devices - which are usually not located at customer site and, thus, not affected by legal requirements - cannot be avoided in some cases. However, AMI data delivering information on the network state at every connection point can enhance grid management applications and provide an easily scalable option for new demand response schemes.

In conclusion, smart meters are suitable for future distribution system management, control and planning by providing relevant data. As described above, there are legal/regulatory and technological challenges that may limit utilising the whole potential of this technology.

LIST OF FIGURES

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11 REFERENCES

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