Working Group on Smart Grids

Smart Grids on the Distribution Level – Hype or Vision?

CIRED's point of view

Final Report

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List of Abbreviations

The following list contains commonly used abbreviations in this report.

AMI	Advanced Metering Infrastructure
AMR	Automatic Meter Reading
CENELEC	European Committee for Electrotechnical Standardization
CIS	Customer Information System
DCC	Distribution Control Centre
DEMS	Decentralized Energy Management System
DER	Distributed Energy Resource
DG	Distributed Generation
DMS	Distribution Management System
DR	Demand Response
DSM	Demand Side Management
DSO	Distribution System Operator
EC	European Commission
EDGE	Enhanced Data Rates for GSM Evolution
FAN	Field Area Network
GIS	Geographic Information System
GPRS	General Packet Radio Service
GSM	Global System for Mobile Communications
HSPA	High Speed Packet Access
ICT	Information and Communication Technology
IEA	International Energy Agency
IEC	International Electrotechnical Commission
IED	Intelligent Electronic Device
ISO	International Organization for Standardization
LMS	Load Management System
LTE	Long Term Evolution
LV	Low Voltage
MIMO	Multiple Input Multiple Output
MV	Medium Voltage
OLTC	On-Load Tap Changer
OMS	Outage Management System
P(H)EV	Plug-in (Hybrid) Electrical Vehicle
PLC	Power Line Carrier

RES	Renewable Energy Source
RTU	Remote Terminal Unit
SCADA	Supervisory Control And Data Acquisition
SG	Smart Grid
SGAM	Smart Grid Architectural Model
SM	Smart Meter
TSO	Transmission System Operator
UMTS	Universal Mobile Telecommunications System
V2G	Vehicle-to-Grid
VPP	Virtual Power Plant

Summary of the report

The answer to the Working Group's question "Smart Grids on Distribution Level – are they Hype or Vision?" is clearly and with no doubt given by the work of the last two years summarized in this report: Smart Grids on distribution level are not just a Hype and they are much more than a Vision. They have already become reality in many current, practical installations in the distribution grids all over the world and they will be an absolute mandatory instrument to pave Europe's and maybe one day the world's way into a low carbon and renewable energy future. Moreover they will help to reduce the transformation costs of the distribution grids and therefore of the whole energy supply system into the renewable future.

The main drivers towards, needs for, use cases, functionalities and technical solutions in Smart Grids presented in this report have been derived from detailed analysis of more than fifty Smart Grid projects in Europe and they show the actual state of the art in this rapidly developing field.

Nearly all projects are driven by the integration of more and more renewable and decentralized generation units into the system, accompanied by the integration of electric vehicles and storage units, while maintaining or even improving the quality and reliability of supply. To establish open energy markets for private and industrial customers, producers and "prosumers", including demand side management, is also an important objective. Therefore the expression "Smart Grid" is in most projects not strictly related to grid issues themselves, but as well includes "Smart Market" objectives and themes.

Functionalities and use cases following the drivers are much more automation on the medium and even low-voltage level, the utilization of advanced metering infrastructure, demand response, generation management including virtual power plants and storage units as well as the operation of microgrids.

To realize the functionalities, a large number of widespread technical solutions in the field of more and more decentralized control systems, protection, communication, new grid components and planning criteria have been developed. In particular, the right communication techniques are mandatory for the success of Smart Grids, since all the intelligent devices have to exchange data and therefore "talk to each other". Another key factor is to keep the enormous amount of data on the distribution level up-to date and uniform with an acceptable amount of effort.

Despite all the development and euphoria around the Smart Grids, most of the technical solutions and devices are still in pilot project status. Much further research and development is needed to establish them as standard tools for grid operation and to safely introduce the individual developments to a still reliable and trustful future supply system. Therefore standardization is mandatory and one main key factor for success. The state of the art of European and International standardization is described in this report, too.

Finally the work of the last two years shows that many projects all over Europe and the world are working more or less on the same challenges and opportunities. This emphasises the need for organizations like CIRED to bring together all the experts on distribution grids, enable them to share their knowledge and expertise and therefore help them to move forward into a smart distribution grid future.

Markus Zdrallek, convenor of the Working Group, May 2013

1 Introduction

1.1 Background and Scope of the Working Group

Since several years, the energy supply business in Europe faces enormous changings never seen before with the distribution grids in the centre of this transformation. The main "official" European driver of the changes is the challenging 20-20-20-agenda of the European Union [1]. It will strongly and sustainably influence the energy market in Europe during the next decade. Especially the goal to "generate 20% of the overall energy consumption in Europe from renewable sources" can only be reached if the electricity consumption is increased significantly (e.g. by electric vehicles or heat pumps) and the higher consumption is generated substantially by renewable sources. Leading European utilities expect that the mean electricity consumption of a standard household will increase from about 4.000 kWh per year today up to 12.000 – 15.000 kWh in 2020. Furthermore, load peaks during the year will be much more distinct since rapidly changing electricity prices will influence customers' consumption behaviour significantly and much more small "green" generation will feed directly into the distribution level.

What does all this mean for the electricity distribution grids?

If the electricity consumption and the number of decentralized generators increase dramatically, the additional need for capacity can be solved in two possible ways: The first – simple but very expensive – way is to increase capacity by doubling or tripling existing infrastructure like cables, transformers etc. especially at the low and medium-voltage level. The second – intelligent – way is to utilize today's grid capacity more efficiently by installing control intelligence in those voltage levels or in other words to establish "Smart Grids".

Therefore "Smart Grids" are the main subject of today's discussion about distribution grids in the future. There is a real hype regarding this topic, but in a quite unstructured and disorientated way. Since we have seen many hypes (like fuel cells, power line communication and so on) come and go in the distribution grid business in the past, the question to answer is whether and how smart technologies will influence the distribution grids sustainably (in the long term) or whether they are just another hype that will be forgotten in ten years' time. Although a lot of other institutions or associations like CIGRÉ or Eurelectric are already working on this topic there is still a need for definition, structure and description of the "state of the art" especially for distribution grids.

Figure 1—1 – as one of various attempts of definition – describes the wide field of all subjects summarized under the topic of "Smart grids" in the energy supply business.

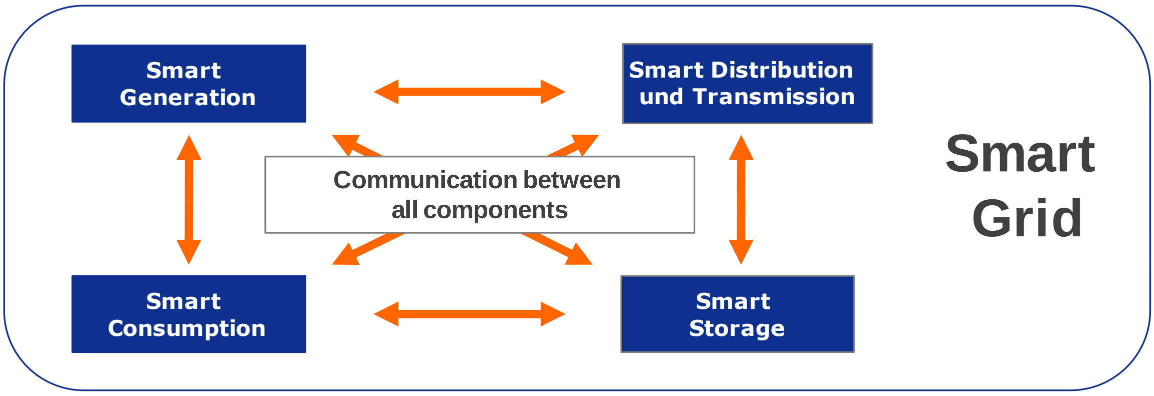


Figure 1—1: Smart Grid definition and roles according to [2]

The Working Group and so this final report strongly focuses on the role of "Smart Distribution Grids" in the smart environment. All others aspects – Smart Transmission Grids, Smart Generation (including renewable generation), Smart Consumption (including Smart Meters, Smart Houses and E-mobility) as well as “Smart Storage” – are only considered in so far as they touch the main purpose of the Working Group.

1.2 Structure of the final report

The final report of the Working group consists of three main parts:

The first part (Chapters 2 and 3) describes the main drivers and the actual need as well as concrete use cases for Smart Grid applications on distribution level. The collection of Smart Grid projects all over Europe given in Chapter 1.3 and in the appendix show that many drivers are common in Europe, but some differ due to the specific situation in the countries. The main drivers for Smart Grid applications at the distribution level are:

- Integration of renewable energy/dispersed generation
- Connection of huge numbers of e-vehicles (including V2G-technologies)
- Establishing storage units
- Increase of energy efficiency
- Establishing energy markets or Demand Side Management
- Increasing reliability and quality of supply
- Reduction of operational and investment costs

The second part (Chapter 4) gives today’s “State of the Art” of technical Smart Grid solutions in Europe. It starts with the aspects of centralised and decentralized control systems as well as the technical possibilities of load and generation control, and continues with the influence of Smart Grids on future protection systems. Since communication is the backbone of all Smart Grid applications the main available communication technologies (power line carrier, wireless communication etc.) with their advantages and disadvantages are discussed including the experiences of several field tests. Furthermore the security considerations of the communication to avoid illegal access to systems or data are illustrated. Finally the (additional) demand of data for smart distribution grids is described.

The third part (Chapter 5) finally presents the “State of the Art” of standardisation of smart distribution grids. European as well as international attempts on standardisation are covered, while national standardisation activities are neglected.

1.3 Proceeding of the Working Group

1.3.1 Data Collection

The work of the Working Group started with the collection of significant Smart Grid projects at distribution level in Europe. The collection was carried out with a uniform project portrait template including all relevant information like project title, main objectives, partners, schedule, region, as well as references or download possibilities. The uniform project portrait template is shown in the appendix.

The result of the collection was a database of about 50 Smart Grid projects from about fifteen countries all over Europe. Many of them are local or national projects, while some are realized with partners across national boundaries or even as EU-wide projects. Figure 1—2 gives an overview of the analysed Smart Grid projects. All project portraits are included in the appendix of this final report.

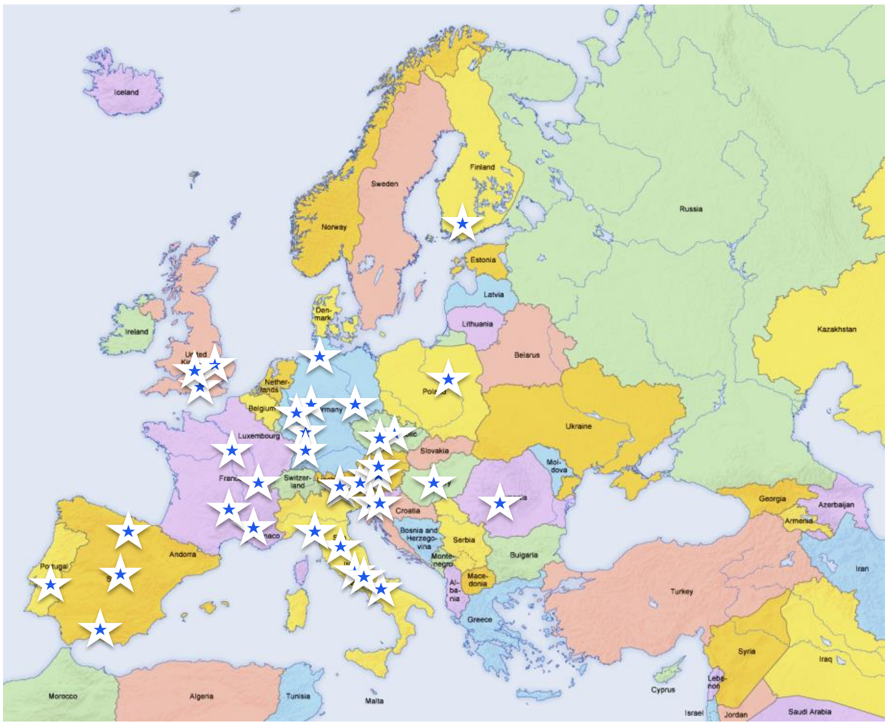


Figure 1—2: Analysed Smart Grid projects spread over Europe

Although the collection was done very extensively and accurately with contributions from all members of the Working Group from different countries it is – of course – not "complete" since not all European countries were represented in this Working Group. The goal of the data collection was not to achieve a complete database of all projects in Europe, which is nearly impossible, since an enormous number of different Smart Grid projects are running in Europe with new ones starting every month. The idea was rather to analyse as many projects as possible in order to get an overview of the main goals, themes and objectives covered by the projects.

However, an up-to-date and much more complete Smart-Grid-project-collection all over Europe is given in the current JRC Report [3]. Figure 1—3 shows the investments in Smart Grid projects in the European countries according to the JRC Report [3].

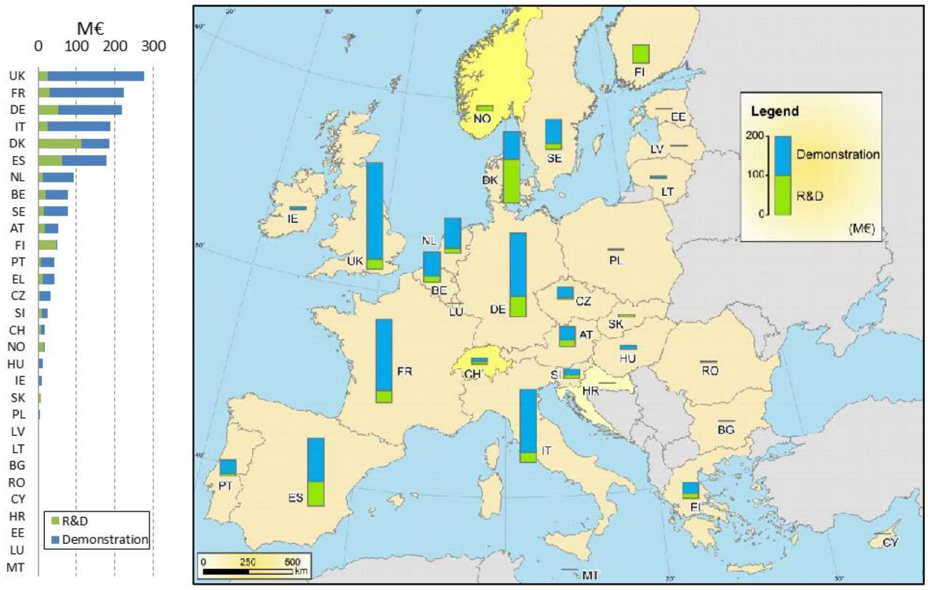


Figure 1—3: Investments in Smart Grid projects related to the European countries [3]

1.3.2 Main objectives, drivers and contents of Smart Grids projects

The collected database of projects was analysed very accurately by screening the submitted project portraits as well as additional information like published papers or web presentations, searching for relevant common subjects in the different projects. According to those subjects representing the main objectives, drivers and contents of the projects a categorization scheme for the relevant topics has been developed.

The categorization scheme consists of eight main categories in all. Four categories are related to the demand or the drivers for Smart Grids, another four categories are related to the technical solutions making Smart Grids possible.

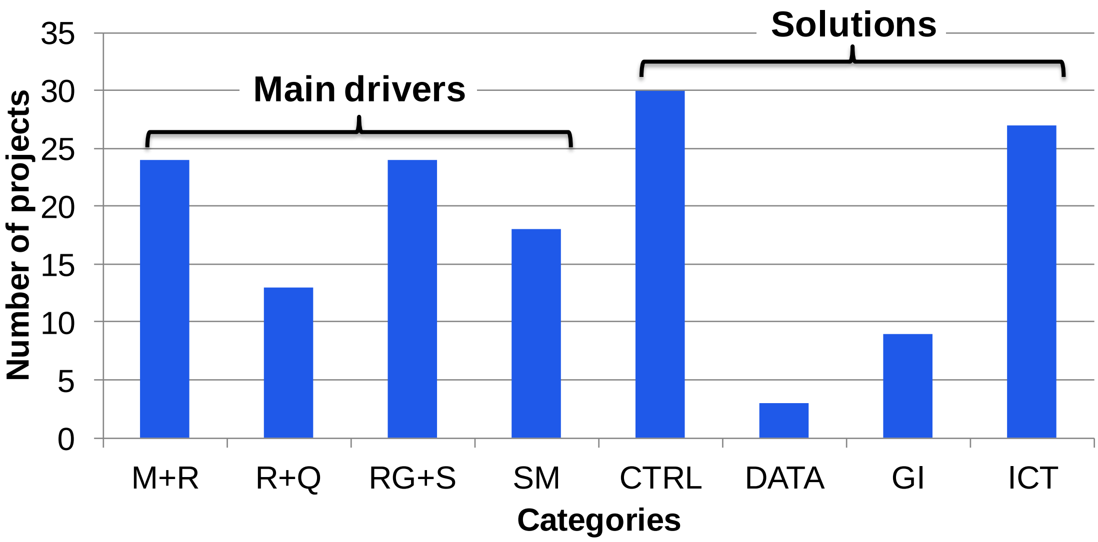
The main categories of drivers of Smart Grid applications in Europe are:

- Integration of renewable and distributed power generation, energy storage and e-vehicles
- Energy markets and regulation
- Smart Metering
- Reliability and power quality

The main categories of technical solutions of Smart Grid applications in Europe are:

- Control techniques
- Information and communication technologies
- Grid infrastructure
- Data warehousing and data demand

Figure 1—4 gives an overview of the number of projects in each category. Most projects cover more than one aspect and therefore are in included in more than one category on the drivers as well as on the solutions side.



CTRL	Control Techniques	**ICT**	Information and Communication Technologies
DATA	Datawarehousing	**R+Q**	Reliability and Power Quality
M+R	Energy Market and Regulation	**RG+S**	Renewable Power Generation and Energy Storage
GI	Grid Infrastructure	**SM**	Smart Metering

Figure 1—4: Categorization of Smart Grid projects

Looking closer on the main drivers it can be seen that most projects deal with the establishment of an open energy market within the given regulation framework (category M+R). The goals are widespread from including more small participants into the energy trading system over time-depending energy tariffs up to the implementation of a common "energy market place". Those projects are often associated with the rollout of smart meters, including communication infrastructure, over a larger grid area as a vehicle for implementing new tariff-structures or market places. These are drivers from the markets point of view.

The other two main drivers are associated with the distribution operator's role. He has to ensure the integration of more and more renewable generation, e-vehicles and storage units and so on into the grid (category RG+S). Furthermore he has to keep the system (the distribution grid) running in all situations without losing or even with improving reliability and quality of supply (category R+Q). The goal to provide a running system, whatever a costumer, a producer or a trader expects from the distribution grid, is the main driver from the distribution grid operator's point of view.

The other main focus of the projects is on the practicability of technical solutions. Nearly all projects try to find a suitable communication technology since communication is the backbone of every Smart Grid application as pointed out before. This comes along with search for appropriate control schemes and techniques. Two different basic control schemes are competing:

- The – traditional – centralised approach, where all data is transferred to large control centres which take all decisions and give all control instructions. This approach comes along with an enormous demand of communication.
- The new approach in which parts of the distribution grid (e.g. a low-voltage grid) are controlled and self-governed by autonomous devices, while very little data is submitted to the control centre. This approach limits the communication effort.

Another aspect in the solution area of the analysed Smart Grid projects is the general grid infrastructure. In this case, the field of research is whether and how the implementation of Smart Grids affects the basic grid structure or the design of the primary equipment (cables, transformers etc.). The question – for example when connecting more and more renewable energy generation units to the grid – is how to combine primary and secondary equipment in the best and cheapest way to achieve maximum additional grid capacity.

1.3.3 Content of the Working Group and the final report

The scope of the Working Group as well as the content and structure of the final report have been derived from the analyses of the main objectives, drivers and characteristics of the collected Smart Grids projects described in chapter 1.3 since they define the "State of the Art" of Smart Grids in Europe. Therefore the final report consist of the three main parts given in chapter 1.2 with the first part (Chapters 2 and 3) representing the "driver"-categories and themes, while part 2 (Chapter 4) handles the "solution"-categories.

As pointed out before, according to the mandate on the Working Group only those projects, drivers and solutions which are strongly related to "Smart Distribution Grids" have been taken into account in the further work.

2 Main drivers/Need for Smart Grid applications

For the International Energy Agency (IEA) Smart Grid is seen as an essential development for the global community to achieve goals for energy security, economic development and climate change mitigation. Smart grids enable increased demand response and energy efficiency, integration of variable renewable energy resources and electric vehicle recharging services, while reducing peak demand and stabilising the electricity system [4].

One important driver for Smart Grid is the increasing share of electricity in the overall world energy consumption (from 9.4% in 1973 to 17.3% in 2009, see Figure 2—1), which will further increase. Thus in both transmission and distribution networks higher loads can be expected, resulting in an increasing demand for electricity generation. The generation can be centralized at transmission level as well as distributed (or dispersed) at distribution network level. To fulfil the global CO_2-reduction goals, an increasing share of the electricity needs to be provided by renewable energy resources (RES). Within the IEA Implementing Agreement ENARD (Electricity Networks Analysis Research and Development) for electricity distribution networks the following drivers for Smart Grids in distribution networks were identified [5]: the continuously increasing share of distributed generation (DG) and the increasing electricity demand.

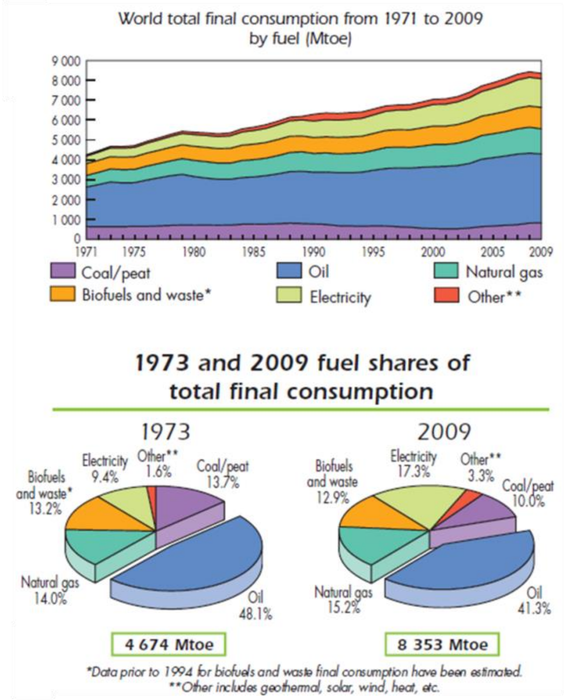


Figure 2—1: Development of the world primary energy consumption [6]

On 12th of December 2008 the European parliament agreed on a climate change package [7]. This includes the following targets until the year 2020, also known as 20-20-20 goals or 20-20-20 agenda:

- a 20% reduction of greenhouse gas emission of 20%
- a 20% improvement in energy efficiency
- and a 20% share of renewable in the EU energy mix

The three goals are strongly interdependent and cannot be seen fully independent from each other. The share of renewable energy resources can be increased much easier if the energy consumption is going to be reduced in parallel. Both measures contribute to the reduction of CO_2 emissions. Concerning electricity networks the most challenging issue is the integration of a high share of electricity generation, based on renewable energy resources, and related solutions to maintain the high quality of supply in the system.

The European Technology Platform requires from Smart Grids to be the future electricity network that meets the needs for Europe's future in the following way [8]:

- Flexible: fulfilling customers' needs whilst responding to the changes and challenges ahead
- Accessible: granting connection access to all network users, particularly for renewable power sources and high efficiency local generation with zero or low carbon emissions
- Reliable: assuring and improving security and quality of supply, consistent with the demands of the digital age with resilience to hazards and uncertainties
- Economic: providing best value through innovation, efficient energy management and "level playing field" competition and regulation.

The related main driving factors in the move towards Smart Grids are [8]:

- The Environment: measures that will enable the EU to meet its targets
- The European Internal Market: the internal market is expected to provide benefits to the European citizens such as a wider choice of services and downward pressure on electricity prices.
- Security and Quality of Supply: countries without adequate reserves of fossil fuels are facing increasing concerns for primary energy availability. Furthermore, the ageing infrastructure of Europe's electricity transmission and distribution networks is increasingly threatening security, reliability and quality of supply.

The individual components influencing those driving factors are illustrated in Figure 2—2.

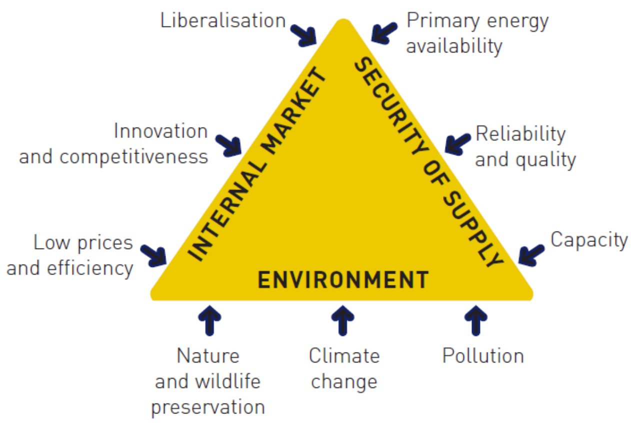


Figure 2—2: European Driving Factors for Smart Grids [8]

The European Regulators Group of Electricity and Gas (ERGEG) identified two main drivers for the development of Smart Grids: The European legislation for carbon reduction and energy efficiency, as a macro driver and specific needs of network users that will result from this legislation, referring to i) large-scale renewable energy sources, ii) distributed generation, iii) end-user participation, iv) market integration and v) improved operational security [9].

For the Union of the Electricity Industry (EURELECTRIC) the Smart Grids is felt to be a necessity for the integration of distributed generation, renewable energy sources and plug-in (hybrid) cars into the electricity grid. Utilizing Demand Side Management (DSM) for improvements in overall system efficiency (such as avoiding investments in peak generation) and customer tariff systems with incentives is a driver. In addition, increasing flexibility in network operation (Distribution Management System - DMS, etc.) as well as optimisation between economic issues including profitability and regulation schemes, and technical related aspects like investments and network operation are significant drivers [10].

The US Department of Energy sees great challenges in the electricity system due to rapidly increasing demand and underinvestment in the electricity system. The drivers and the challenges which should be solved by Smart Grid are [11]:

- Reliability: Avoiding blackouts
- Efficiency: Support energy saving
- Security: The grids centralized structures can by attacked
- Environmental and Climate Change: Reducing the carbon footprint by introducing renewable sources
- Global Competitiveness

For the CIRED report on Smart Grid on the Distribution Level the following key drivers for Smart Grid were identified:

- Increase in energy demand
- Growing share and integration of renewable energy and dispersed generation
- The introduction of electro-mobility
- Storage integration
- Increase of energy efficiency
- Energy market and demand side management
- Reliability and Quality of Supply
- Optimization of operational and investment costs

Of course the main drivers for Smart Grids can vary from country to country as well as from continent to continent. In Europe drivers are mainly related to environmental reasons in terms of CO_2 reduction. In Asia the driver is to overcome the increasing electricity demand due to the still fast growing economy, and in North America and especially the U.S. it is security of supply related to increasing peak loads and aging infrastructure.

2.1 Integration of renewable energy/dispersed generation

For future electricity networks the most challenging issue is the integration of a high share of electricity generation, based on renewable energy resources, and related solutions to maintain the high quality of supply in the system. Due to the current energy related framework conditions and technical developments, the penetration of Distributed Energy Resources (DER) and especially Distributed Generation (DG) in distribution networks increases continuously and it can be expected that this increase will continue in the future (see Figure 2—3). These results in a growing density of electricity resources within distribution networks, where technical issues related to the bidirectional power flow, reliability aspects (power quality and continuity of electricity supply), stability aspects, network capacity, the management of network, energy and load are becoming increasingly important. The common strategy to view distributed electricity production as a “negative” load and the therefore resulting in a ”fit & forget“ philosophy is not a sustainable and applicable solution for the future. New solutions for an active integration of DER and to maximize the utilization of the existing electricity network infrastructure are required.

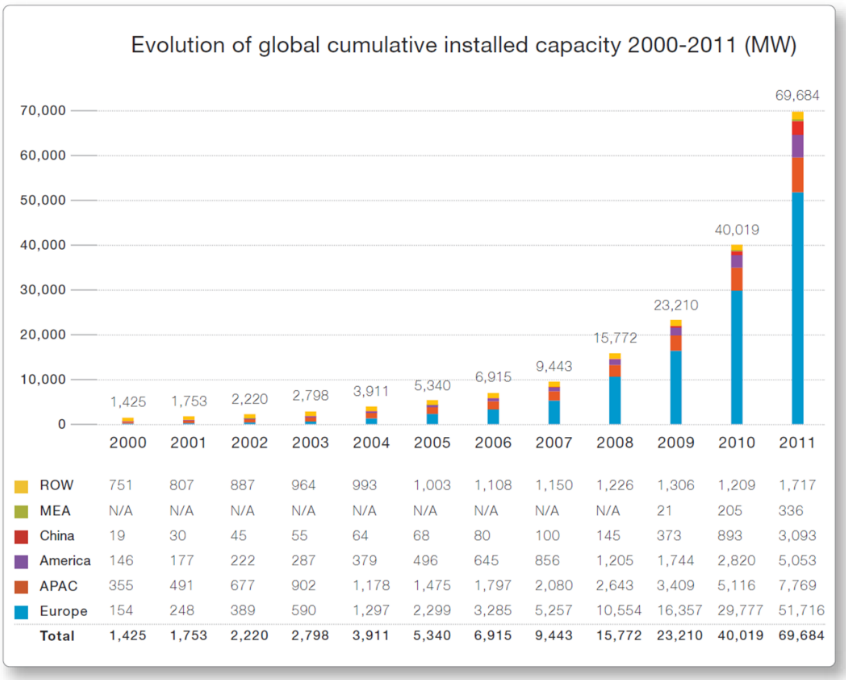


Figure 2—3: Evolution of the cumulative installed PV capacity [12]

2.2 E-mobility (also V2G-technologies)

One opportunity to reduce the CO_2-emmisions and the dependency on fossil fuels in transport is the electrification of the transport sector. During recent years, all over the world a lot of effort has been put into the development of electric vehicles and battery systems. On the one hand the massive introduction of e-vehicles in the electricity system will result in a significant increase of peak demand as well as energy consumption but on the other hand it might give the opportunity to make use of the additional storage capacity via vehicle to grid (V2G) technologies. Smart grid technology can enable charging to be carried out more strategically, when demand is low, making use of both low-cost generation and extra system capacity, or when the production of electricity from renewable sources is high. Over the long term, Smart Grid technology could also enable electric vehicles to feed electricity stored in their batteries back into the system when needed. Figure 2—4 shows a scenario for the global deployment of electric vehicles and plug-in hybrid electric vehicles developed by the International Energy Agency [13].

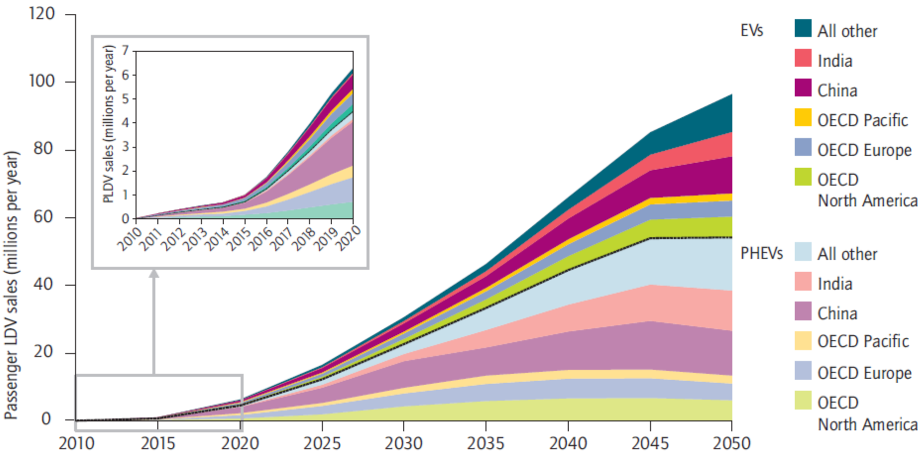


Figure 2—4: Global deployment of electric vehicles and plug-in hybrid electric vehicles [13]

2.3 Storage

Electricity generated by renewables, such as wind and solar is based on variable resources. Electricity storage can support local and regional balancing of supply and demand and therefore enable a higher share of renewable energy in the electricity mix. The principal electricity storage technologies include hydropower with storage, compressed air energy storage, batteries, hydrogen-based energy systems, secondary batteries, flywheels, super capacitors, and superconducting magnetic energy storage. Each technology with their specific characteristics in capacity and power can support different timescales for power balancing.

Electricity storage can be seen as a tool used for managing variability and capacity in the Smart Grid. The evolution of the Smart Grid will depend on cost effective energy storage, particularly in the early stages while other distribution and demand-side management solutions are being developed, adopted and implemented. A Smart Grid is required to serve solutions to actively integrate different storage technologies in electricity networks.

2.4 Increase of energy efficiency (e.g. by use of Smart Metering; EC 20-20-20 targets)

As introduced above, increased energy efficiency is one key aspect to fulfil the global CO_2 Reduction goals. A Smart Grid can support energy efficiency by providing more information about the actual power flows in the system and the related electricity demand. In the European climate change package a 20% improvement in energy efficiency is required. In 2006 the European directive on energy end-use efficiency and energy services was introduced. One of the measures to ensure the energy efficiency is the introduction of electronic metering and related informative billing [14].

Smart meters can enable two-way flow of information, providing customers and also utilities with data on electricity price and consumption, including the time and amount of electricity consumed. Automated meter reading can provide a wide range of additional functionalities [4]:

- Remote consumer price signals, which can provide time-of-use pricing information.
- Ability to collect, store and report customer energy consumption data for any required time intervals or near real time.
- Improved energy diagnostics from more detailed load profiles.
- Ability to identify location and extent of outages remotely via a metering function that sends a signal when the meter goes out and when power is restored.
- Remote connection and disconnection.
- Losses and theft detection.
- Ability for a retail energy service provider to manage its revenues through more effective cash collection and debt management

Additionally smart meters and the related information and communication infrastructure can and should be used for network monitoring and network control purposes and hence can support new Smart Grid control approaches.

2.5 Energy Market/Demand Side Management

Along with the opening of the power markets in the 1990’s, the network operator’s activities were unbundled from generation activities. Before the opening of markets, the network operators were often integrated with the power production companies and had full control over the majority of the power production. The network operators could at all times optimize the power production to the load demand. To overcome the variability of renewable based electricity generation in future, a paradigm shift might be possible by changing the philosophy from one where production follows load to a future power system where also load follows renewable energy sources (RES). That will require demand side management measures at all network levels.

In a free market generators and consumers are operating their components mainly according to market incentives. Smart Grids are expected to be the key to handle both market driven operation and network driven integration considering local and regional congestions in the electricity networks, to maintain reliability and security of supply in the overall system.

2.6 Reliability/Quality of Supply

Growing electricity consumption and recent system failures have focused attention on the role that Smart Grids can play in increasing electricity reliability – especially by increasing system flexibility [4]. All over the world reliability and quality of supply are seen as key drivers for the introduction of the Smart Grid [4], [8], [9], [10], [11]. The starting conditions concerning reliability and quality of supply vary from region to region. In developed countries the reliability and quality of supply is usually at a high level. Here Smart Grids should be the solution to maintain this high level with the presence of a large share of renewable technologies and increasing electricity demand combined with an aging infrastructure. In emerging economies as well as in developing countries the driver for Smart Grids is to improve the reliability and the quality of supply.

2.7 Optimization/Reduction of operational and investment costs

From an economic perspective the reduction or optimization of operation and investment cost is a major driver for Smart Grids. The related technologies and control approaches should deliver solutions which are more cost efficient (less expensive) as related network reinforcement measures and state of the art network planning and operation approaches. In that context the maximum utilization of the existing network infrastructure is a key driver. The Smart Grid is required to meet the above mentioned needs with as low as possible levels of investment and future operational costs.

ERGEGs opinion [9] is that in the longer term Smart Grid solutions are expected to significantly reduce the costs of supporting the expected growth of alternative renewable generation. Smart grid investments are not comparable with the “fit and forget” strategy because the benefits are estimated in very different ways. The integration of renewable energy sources (RES) in the network is seen as a challenge but at the end of the day the benefits of better controllability, efficiency, quality and security of supply will justify the required investments.

3 Use Cases and Functionalities of a Smart Grid

3.1 Introduction

In this chapter several use cases of Smart Grid applications and solutions for distribution networks are shown and typical functionalities of each use case is explained. Use cases describe tasks that a customer or end users will accomplish using the solution, and includes important actions, technologies and requirements that are part of the Smart Grid applications.

Here for each use case the problem is described and the target of the solution is specified. Key technologies necessary for the realization are listed and the resulting benefits as well as possible customers or users of the solutions are described.

3.2 Integration of distributed Renewable Energy Sources (RES)

Use Case: Integration of distributed Renewable Energy Sources (RES)	
Description:	The integration of fluctuating Renewable Energy Sources (RES) and Distributed Energy Resources (DER) into today's distribution networks can result in various challenges for network planning and operation. On one hand changing power flows due to large shares of distributed generation in the low and medium voltage networks will affect the voltages, which can result in voltages violating the operational steady-state maximum and minimum voltage limits. On the other hand the capacity of DER generation highly exceeds the load already today in some distribution networks, e.g. in Southern Germany. The ratings of the network components are not designed for these high power flows feeding back into the overlaying network. Thus overloading of cables, overhead lines and distribution transformers can be a serious problem resulting in large investments, which are necessary to strengthen the networks and to ensure security of supply.
Targets:	The target of Smart Grid solutions and technologies is to limit the impact of DER generation on the network components, to ensure safe operation of the grid and to increase the amount of DER generation, which can be connected to the distribution networks while - minimizing the investment for strengthening the grid by intelligent operation of the network and control of active network components, loads and generation - ensuring high power quality of supply so that no customers are disturbed by the impact of RES on the power supply. - Market integration. RES should not be exposed to market risk if it cannot offer flexibility. Market needs to adapt to grid constrains and typology.
Key functionality:	The following technologies and solutions can be applied: - changing the network structure and operation concepts, e.g. by using open or even closed ring structures instead of simple radial networks, by increasing the MV voltage in selected parts of the network or by adding additional MV substations where necessary - demand side management, controlled generation, electrical vehicle or distributed storage devices to locally balance load and generation and to control the power exchange with the connected MV and HV networks. Distribution energy management systems (DEMS) can help manage DER, load and energy storage, which will increasingly be deployed within distribution systems. - Controlling the amount of power injected by DG RES. Grid curtailment is compulsory in order to guarantee grid stability - installation of active components to replace passive components to control the

	voltage in the distribution network. These components can for example be controllable reactive power from converters of generation sources, regulated distribution transformers, MV power electronics, booster transformers, energy storage devices, etc. - In normal situations, DSO will control RES accordingly with market negotiations. In abnormal or emergency situations, DSO should totally control RES - Additionally ICT technologies have to be applied in most cases including centralized or decentralized intelligence and decision making algorithms.
Benefits:	By influencing the active and reactive power flow by active components, situations of equipment overloading and voltages exceeding operational limits can be reduced or even fully eliminated in order to guarantee grid stability. Thus the need for network extension and strengthening and therefore the necessary investment can be greatly reduced.
Customer and user:	Utility/DSO, customer, network owner, market

3.3 Distribution Automation

Use Case: Distribution Automation	
Description:	Distribution networks are under high pressure to meet requirements for converting their conventional static grids into modern and dynamic Smart Grids. In particular, the increasing occurrence of Distributed Energy Resources (DER) is influencing this trend, as well as the need to improve the quality and reliability in MV and LV networks. Ever-growing cost pressure adds to the requirements on operation and maintenance. As Smart Grid capabilities, such as smart metering, demand side management, demand response, or the integration of distributed energy resources and plug-in electric vehicles (PEVs) are deployed, the automation of distribution systems becomes increasingly more important to the efficient and reliable operation of the overall power system. New requirements are arising for automation, monitoring control and protection of distribution substations and ring main units (RMUs). These requirements are most suitably supported by consistent and flexible system solutions, which are scalable for different applications.
Targets:	Automation in the distribution field allows utilities to implement flexible control of distribution systems, which can be used to enhance efficiency, reliability, and quality of electric service. The main targets of automation of distribution networks are to implement monitoring of the network status and communication of the measured values to improve observability and controllability of the network through telecontrol of IEC deployed in the network. Thus detection and clearing of faults or disturbances as well as actions to restore power supply to interrupted customers can be improved.
Key functionality:	Distribution Automation includes - Real-time field equipment monitoring; Phasor measurement units and other sensors that increase wide-area situational awareness; - Introduction and control of network components and active components, e.g. regulated distribution transformers, reclosers, generation converters or loads, etc. - Bi-directional communication channels from secondary equipment to the control room and vice versa - Integration of field equipment with back office and information systems, e.g. measurements or protection devices.
Benefits:	The anticipated benefits of distribution automation and management include for example increased reliability, reductions in peak loads and equipment loading, and improved capabilities for managing distributed sources of renewable energy or electric vehicles. All these benefits will translate in a reduction of interruption time and

	minimizations of the number of clients affected by an outage.
Customer and user:	Utility/network operator, customer

3.4 Advanced Metering Infrastructure

Use Case: Advanced Metering Infrastructure	
Description:	Utilities are focusing on developing Advanced Metering Infrastructure (AMI), i.e. Smart Meter and Meter Data Management, to implement demand side management, residential demand response, aggregated control of distributed generation and to serve as the chief mechanism for implementing dynamic pricing solutions. It consists of the communications hardware and software and associated system and data management software that creates a two-way network between smart meters and utility business systems, enabling collection and distribution of information to customers and other parties, such as competitive retail suppliers or the utility itself. AMI provides customers dynamic pricing of electricity and it can help utilities achieve necessary load reductions. This allows distribution system operators (DSO) to optimize essential key processes and offer new services and data to their customers, both on the supplier as well as the consumer side.
Targets:	Distribution network operators seeking to ensure economic success and expand further under these framework conditions must optimize existing network operation processes and develop new fields of business. Smart metering and advanced metering data management provides the ideal conditions for doing so. It combines metering and management of distribution networks in one system and was developed explicitly for the special requirements of the liberalized energy market.
Key functionality:	As a complete solution, advanced meter data management comprises all necessary hardware and software components for the following applications: - Acquisition of all consumption data for electrical energy for tariff and special contract customers - Remote control and load-switching possibility of customer load (if agreed in a services contract) - Recording and documentation of quality of supply (meter: voltage tolerances, short-term failures, long-term failures, power quality) - Creation of an open communications platform for the integration of multi-utility metering (gas, district heating, water) and additional services (Home Automation) - Recording of unauthorized power tapping and manipulations on the terminal devices (such as meters) - Remote control of the transformer stations, RMUs and the complete distribution network infrastructure - Single and three-phase meters for direct connection to low voltage network; Active and reactive energy and power measurement (consumed and produced); Multi tariff and capable of operating simultaneously with two-tariff structures; Load profiling; Maximum demand registration; Power control management, with capability to remotely change maximum demand threshold and connect/disconnect supply; Demand management; Events registration and alarms management; Anti-fraud detection; Quality of Service logging; - Local communication interface to enable communication to in-house equipment
Benefits:	The installation of smart meters and advanced meter data management systems should allow for - Automated customer processes (billing, change of tariff, data collection, etc.). - Implement various tariff models and acquire data on supplied/imported reactive energy. - Record the capacity utilization of individual primary equipment like line

	sections and transformers in order to optimize maintenance intervals, minimize line losses (e.g., by moving open/break points), and obtain additional data for planning expansion of the power network. - Minimize down times by acquiring and diagnosing errors. - Integrate small, decentralized energy generation plants into the distribution network for billing and automation purposes. - Record and document the customer supply at the point of supply (in the meter) for the purpose of providing evidence and for planning the power network. - Support disturbance management and clearing in the event of a fault in the network.
Customer and user:	Network operator, customer, generation, energy trader

3.5 Energy Storage

Use Case: Energy Storage Devices	
Description:	Utilization of Renewable Energy Sources (RES) on a large scale leads to new challenges in grid stability, as a result of the intermittent behaviour and forecast errors resulting in unbalances between demand and generation. Distribution grid operators face the challenge of providing enough balancing power to ensure a uniformly high-quality power supply. In industrial networks energy-efficient processes and the reduction of energy costs are of high importance. Part of their energy costs depend on the maximum load within a certain timeframe. Exceeding the agreed maximum load only once can cause high costs. Additionally a short interruption of energy supply can disturb the industrial processes and may lead to a complete failure of production plants, which has a noticeable financial impact.
Targets:	Energy storage devices can be applied in distribution systems for achieving several targets: - Participation on the market for primary control power and energy - Storage can act like generators of some ancillary services as load shifting, local voltage control and primary frequency control - Influencing the active power flow and voltage behaviour in distribution networks to minimize investments for strengthening the grid infrastructure - Temporary islanding operation of island networks and industrial grids after disconnection from the utility network - Improving reliability and security of supply - Reduction of temporary load peaks
Key functionality:	Different energy storage devices can be installed into the distribution and LV network to give the following benefits: - Influence active power flows and limit equipment loading - Provide reactive power support and voltage control - Balancing of load and generation to match power exchange between networks to a forecast or to enable islanding operation of microgrids - Enable participation in the market for primary control power and energy - Act as an important integral part for virtual power plants (VPP) and distribution energy management systems (DEMS) - Black start capability of energy storage - Electrical Vehicles can also act as storage and generator devices. In V2G (Vehicle to Grid) scheme besides the charging, the aggregator controls also the power that EV might inject into the grid; EV have also the capability of providing load shifting and to perform primary frequency control.
Benefits:	Energy storage systems are one solution for a sustainable and reliable supply of energy. Benefits can be the integration of a higher share of fluctuating renewable energy sources into the grid, self-sufficient energy supply for Microgrids and industrial islanded

	networks, or reliable reserve for the industry, buildings and infrastructure facilities.
Customer and user:	Utility/DSO, customer, energy trader

3.6 Microgrids

Use Case: Microgrids	
Description:	The term microgrid defines a grid which can be operated in islanded and utility grid parallel mode with a high penetration of distributed renewable energy sources (RES) - mainly wind and photovoltaic generation. Microgrids include low voltage and medium voltage networks. The generating units are in the range from some kilowatts to megawatts. Installed synchronous generation is typically diesel powered, often installed together with energy storage devices.
Targets:	In systems with autonomous control, each part or component is capable of meeting some control objective without dedicated communication links with other system components. The targets of realizing microgrids are: - independence from (weak) utility grids. - realization of microgrids on islands with no access to utility grids or in rural areas. - minimization in cost of energy supply especially in remote areas or on islands. - reduction of dependency on fossil fuels, like diesel or gas. - reduction of CO_2 emissions.
Key functionality:	Microgrids typically are divided into four subtypes: - utility microgrid - industrial microgrid - military microgrid and - institutional or campus microgrid Microgrids can have different functionalities: - Microgrids offer up to two operation modes: off-grid islanded mode and grid connected or grid parallel mode. - Countries and states with high access to renewable energy resources can integrate a large number of RES into their power generation system. - One of the main challenges in microgrids is the fluctuating generation and the potential absence of a utility grid, which influences power flows, short circuit levels, system dynamics, protection coordination, system reliability and in case of a high number of converter connected generation system harmonics. The fluctuating generation can be balanced by integration of storage devices. Furthermore, communication can improve system reliability. - After a major system blackout microgrids can isolate themselves very fast to ensure secure power supply or they can be quickly restored, since diesel generation which also serves as prime source is usually directly black start capable.
Benefits:	Microgrids offer access to energy in areas with difficult access to a utility grid or to areas which like to reduce their dependency on fossil energy resources. When connected to weak and unreliable utility networks, microgrid functionality can highly increase reliability and security of supply as it can be isolated from any external network in case of disturbances and blackouts. From a political and environmental point of view a “green” region/island also increases tourist attractiveness. Autonomous controls and distributed architectures may improve availability but, at the same time, may reduce energy/power efficiency because there might be a trade-off between meeting the system’s optimal operation points and the optimal operation of individual components
Customer and user:	DSO on islands and regions with no access to utility grids, industrial customers and

	system operators, military and campus networks

3.7 Demand Response and Generation Management

Use Case: Demand Response (DR) and Generation Management	
Description:	Demand Response (DR) can be defined as the changes in electric usage by end-use customers from their normal consumption patterns in response to changes in the price of electricity over time. Further, DR can be also defined as the incentive payments designed to induce lower electricity use at times of high wholesale market prices or when system reliability is jeopardized. DR includes all intentional modifications to consumption patterns of electricity of end use customers that are intended to alter the timing, level of instantaneous demand, or the total electricity consumption. Mechanisms and incentives for generation, utilities, industrial, commercial, and residential customers to cut or shift the usage or generation of electrical energy - During times of peak demand and maximum generation of DER. - To balance generation and demand. - During network congestion or high loading situations. - When power reliability is at risk. - For participating in the energy market or to reduce energy costs. The participant can either control its own consumption in case of larger industrial or commercial units to achieve savings of energy consumption costs, or the customer can alternatively allow the utility to use part of his consumption as controllable load in order to access better tariffs. Generation could temporarily reduce its production. The main goal of demand side management is typically to encourage the consumer to use less energy during peak hours or at times with high in-feed of RES, or to move the time of energy use to off-peak times such as night-time and weekends. Peak demand management does not necessarily decrease total energy consumption, but could be expected to reduce the need for investments in networks or power plants.
Targets:	Thus demand response can be used for optimizing the balance of power generation and load, e.g. in the case of large shares of intermittent RES and not controlled DER. Targets can include - reduced energy costs, - reduced loading of equipment, - reduced investment for strengthening, - increase of power quality, - higher security of supply and - increased system efficiency.
Key functionality:	The following technologies and solutions can be applied: - distributed storage devices to balance local load and generation and to control the power exchange with the connected MV and HV networks - usage of controllable smart appliances at home - Demand response due to dynamic pricing signals Distributed energy management systems (DEMS) including controlled generation and virtual power plants (VPP) as management of DER will increasingly be deployed within distribution systems. Customers' Demand Response (DR) can either be: - manual: they see prices e.g. on a display and decide to shift their consumption; or - automated: their consumption is shifted automatically through technical signals, and based on an agreement established with the supplier. For instance, a customer could decide his/her consumption to be shifted to another time when prices meet a certain level. Additionally ICT technologies have to be applied in most cases to remotely control the demand.
Benefits:	DR aims to reduce electricity consumption in times of high energy cost or network constraints by allowing customers to respond to price or quantity signals.

	By (partly) influencing the consumption and generation, the generation and load can be balanced not only on the transmission system level but also on distribution level and locally by the DSO. Thus power flows can be reduced during times with high demand and high renewable generation, leading for example to - lower equipment loading, - lower voltage variations - better forecast of distribution network demand - lower losses and high sustainable operation - reduced need for network extension and investment in the grids. Demand Response and Generation Management (and also Demand Side Management) will bring benefits for: - Customers: ▪ Increased awareness and savings ▪ Increased participation and economic benefits of personalised and flexible load contracts - Suppliers: ▪ New products and services for customers ▪ Enhanced balancing and hedging opportunities - Network Operators: ▪ Optimize the use and investment in new network assets to relieve constraints ▪ Increased network performance - Generators: ▪ Potentially lower need for investment in peaking generation plants ▪ Reduced need for back-up capacity for RES integration ▪ Diversification of their portfolio
Customer and user:	Utility/operator, customer, energy trader

3.8 Decentralized energy management systems (DEMS) and Virtual Power Plants (VPP)

Use Case: Decentralized energy management systems (DEMS) and Virtual Power Plants (VPP)	
Description:	In parallel with the liberalization of the energy markets, the decentralized generation of electrical power, heat and cold energy becomes more and more important. The generation of these types of energy near to the consumers offers economic and ecological benefits. Distributed energy resources aggregated into virtual power plants (VPPs) will create the provisional interface that is lacking in order to exploit the technical and economic synergies of this multi-fuel, multi-location and multi-owned power station system which could provide various ancillary services (e.g. balancing power and power-frequency control) as an alternative to large centralized power plants and increase the competitiveness of reserve markets; The RES and DER are used to displace energy from conventional power plants but not to displace their capacity as they are not visible to system operators and thus not controllable but relying on stochastic behaviour. If this behaviour remains, it can lead to problematic over-capacity issues and under-utilization of the assets, reduce overall system efficiency and eventually increase the electricity cost that needs to be paid by society.
Targets:	The concept of VPP was developed to enhance the visibility and control of DER to system operators and other market actors by providing an appropriate interface between these system components. A virtual power plant is a collection of small and very small decentralized generation units that are monitored and controlled by a superordinate energy management system that enables to forecast, schedule and control its output. In general, these generation units produce heating and cooling energy as well as electricity to increase the overall efficiency of the whole energy system. They can be based also on renewable generation. Certain approaches also include storage units and

	the integration of the demand side to achieve highest benefits in creating the schedules and to be able to adhere to the schedules also in case of high shares of renewable generation. The DSO task will be to set the infrastructure that will enable producers, customers/"prosumers", suppliers and other service providers to meet on an open market place while giving them more advanced tools to manage their grids. Market integration of RES and participation of RES in system security, including provision of (part of) the ancillary services from DG/RES
Key functionality:	The operation of a virtual power plant requires the following technical equipment: - An energy management system that monitors, plans and optimizes the operation of the de-centralized power units. - A forecasting system for the loads and generation of renewable energy units including weather forecast for RES that is able to calculate short-term forecasts (hours up to 7 days). - An energy data management system which collects and keeps the data that is required for the optimization and the forecasts, e.g., profiles of generation and loads as well as contractual data for customer supply. - A powerful and bidirectional communication of the energy management system with the de-centralized power units. - DSO should be pre-informed of DG forecast, schedules and active dispatch, be able to sectionalize networks and adjust regulation set points in advance. The TSO controls active power of distribution connected DG. The DSO should have control of voltage set points and reactive dispatch on the distribution system (active control of V, Power Factor, Q) - Increased need for network reinforcement to accommodate new DG connections
Benefits:	The advantages of virtual power plants can be: - Increased visibility of the power plant to the distribution network operator - Improved forecasting of RES and thus reduction of costs for balancing load and generation - Improved controllability of the VPP due to aggregation of different small controllable and not-controllable energy sources taking into account forecasting of (load and) generation - Providing new business fields for DER and improving market access
Customer and user:	Utility/operator, DER owners, energy traders

3.9 Electro-mobility

Use Case: Electro-mobility	
Description:	In the future it is expected that internal combustion engine vehicles will be replaced step-by-step by vehicles powered by electricity and batteries (plug-in electric vehicles (EVs) such as electric cars (BEVs) and plug-in hybrids (PHEVs)). The rated charging power is rather low today, but the fast charging and home charging concepts show that connection power and load might increase dramatically, when e-cars will be charged in large numbers. Thus electro-mobility will have a large impact on today's distribution networks, which are not designed for a large increase in connected loads. The increasing load can result in overloading of components in the distribution network as well as large voltage drops, which can negatively affect power quality and nearby customers. Hence large investments for network extension and strengthening will be necessary to enhance the distribution networks.
Targets:	The target of Smart Grid solutions and technologies is to increase the amount of electrical vehicles, which can be connected to the existing distribution networks while reducing the necessary investment for strengthening the grid and while ensuring sufficient power quality.
Key functionality:	Apart from changing the network structure and network extensions, various intelligent

	strategies can be used to influence the vehicle charging process. The following strategies could be used, which are listed here as an example: - limitation of charging power in case of overloading situations - charging depending on an external price signal from the utility - charging processes are controlled to fit the demand to the available DER generation - Vehicle to grid (V2G) behaviour – electric vehicles communicate with the power supply network and with the utility to sell demand response services by either delivering electricity into the grid or by limiting their charging power when necessary. EV have also the capability of providing load shifting and to perform primary frequency control Integration of Electric Vehicles is subject to interoperability with market and revenue cycle services as well as real time distribution operations. ICT technologies have to be applied in the cases described above.
Benefits:	By controlling the charging process of the electric vehicles overloading of installed network components can be eliminated. Thus the need for network extension and strengthening and therefore the necessary investment can be greatly reduced. By using V2G functionality EVs can at least partly act similarly to energy storage devices (see use case "Energy storage") and actively participate in the energy market or in balancing load and generation. DSOs and market can use EVs as storage devices (EVs) and generators of some ancillary services as load shifting, local voltage control and primary frequency control.
Customer and user:	Utility/operator, EV owner, energy trader

4 Technical Solutions/State of the Art Technologies

As result of an evolution of electrical grids to the Smart Grid concept, new functionalities and digital energy applications are expected in an electrical utility, such as smart metering, smart automation and distribution automation that rely on machine-to-machine networking technologies that transfer data to and from smart meters and other actuators and sensors in the field.

There are a number of communication technologies that have been successfully deployed to this end, including private wireless networks, power line carrier, public cellular technologies and others. As the public profile of Smart Grid has risen, so the battle for technological superiority has intensified.

This section presents an overview of technologies that have been successfully deployed to support digital energy applications and grid functionalities.

4.1 Application and Requirements

There are two groups of Smart Grid applications that require a low-cost, reliable and secure network to reach thousands or millions of physical devices: Smart Metering and Grid Automation.

The two have some similar properties when it comes to designing the Field Area Network (FAN; also known as “Local Area Network”, “Neighbourhood Area Network” or “last mile”) such as:

- Modest bandwidth requirements at the endpoint when compared with other modern networks, since most messages only contain simple sensor data and instructions;
- Endpoints that can be geographically dispersed or inaccessible by existing fixed networks;
- A need for high scalability;
- Requirements for high reliability and security, to ensure quality of service and data accuracy, as well as to detect and prevent tampering or malicious attack.

However, each application group also has its own particular requirements and challenges, particularly with regard to latency.

4.1.1 Smart Metering

Low requirements for bandwidth and latency, but there are a couple of exceptions to this rule:

- Real-time demand response in particular requires low latency, which many smart metering networks currently do not offer;
- Multiple endpoints, if aggregated by a data concentrator or gateway, can raise bandwidth requirements for the overall system;

4.1.2 Grid Automation

Grid automation and control applications need much lower latencies than smart metering;

- Outage management and grid protection applications are cited as needing 10-30ms latencies;
- Supervisory control and data acquisition (SCADA) are in the range of 100-200ms;

4.2 Control Techniques

The deployment of distribution system intelligence leaves a key question still open: will distribution control systems have centralized or decentralized architecture in the Smart Grid? The question is still debated and there is no general consensus on which of the two options will have more chances to be widely deployed in real systems.

The term *centralized* implies that the majority of the intelligence and software is located in a central system (e.g., the Distribution Control Centre) where an automatic system (dispatcher) or a person in charge is located. On the other hand, in a *decentralized* architecture the application resides outside the substation premises, in the feeder or in other field location. It is clear that these definitions can create confusion because any advanced and innovative distribution control architecture falls in some extent in both definitions. Indeed, modern control architectures require distributed measurement systems and use intelligent devices (i.e. intelligent breakers and sectionalizers). On the other hand, it should be observed that Human Machine Interface (HMI) is often placed in control centres to enable technical personnel to access the application inputs and outputs for various purposes. To solve the ambiguity of definition, it can be stated that "*centralized*" means the majority of the application logic is in the control centre, and that "decentralized" means the application logic is spread across the system by means of intelligent devices. Four different categories for advanced distribution control applications can be defined [15]:

- **Centralized**: The main feature is that all logic is concentrated in one or more Distribution Control Centres, which is a location staffed by individuals responsible for the operation of the distribution system and for the maintenance of the advanced control application.
- **Substation-centred**: This is considered a decentralized architecture with the application for the control of some feeders installed in the substation that serves those feeders. The location is normally not staffed with persons that use and maintain the control application.
- **Fully distributed**: The vast majority of software and control logic is installed at the location of the controlled device. A fully distributed architecture may be implemented by means of the intelligence available with stand-alone devices. Intelligent devices can operate independently or communicate with other intelligent devices by using "peer-to-peer" communication facilities to exchange local measurements and control signals.
- **Coordinated hybrid**: This architecture is a balanced, compromise architecture between the centralized and fully decentralized architectures. The role of central system is to coordinate the local actions at a wider and higher level to ensure security of operation in any circumstance and to allow the distribution system be better integrated with TSO. Asset management can be improved by this architecture.

The choice of the architecture is not a simple task because many different contrasting factors should be considered making the problem of the optimal choice of the advanced control architectures a complex multi-objective problem. The most common factors are security and safety, speed, complexity and budget. *Security and safety* requires the utility-related rules embedded in the advanced control architecture. *Speed* refers to the maximum allowed latency between the event and the associated control system response. The speed range is wide, spanning from a few milliseconds to several minutes depending on the particular event and control function. *Complexity* refers to the level of flexibility that must be included within the control system. The greater is the frequency of changes and modifications of the control architecture as an answer to system changes, the greater is the complexity of the advanced distribution control. Applications with a logic that remains static and does not frequently change are not considered complex (i.e. those that are based on static rules). *Budget* is a fundamental feature since most of the DNO are regulated and committed to demonstrate cost efficiency. Generally speaking, architectures with low complexity are better suited to centralized systems whereas very low-latency functions are more adapted to fully decentralized architectures. Besides the aforementioned four factors, other aspects should be considered. The **number of feeders to be controlled and automated** is an important factor. For instance with reference to the Fault Location Isolation and Restoration Services (FLISR) normally the worst performing feeders are chosen for automation and, if the number of these feeders is small, the decentralized architecture might be preferable to avoid the costs related to centralization. For safety and workforce reasons the distribution operator must be aware at any time about the status of the network and must know all switch actions that change the network topology (**Operator Visibility).** All applications that can change or modify the status of the network are natural candidates to be centralized. The availability of **reliable communication paths** can dictate the architecture of control systems. For example, if field devices cannot communicate directly with the substation a substation-centred architecture will not be a good choice or might be too expensive. Finally communication system must comply with the functions implemented in the control systems (e.g., FLISR automation cannot be based on power line carriers). The availability of **commercial products** (off-the-shelf) is also an element for the choice of the architecture. Currently, the majority of advanced control systems for Smart Grid applications are centralized or substation-centred, but many research and demonstration projects are exploring capabilities and benefits of fully decentralized agents and a growth of peer-to-peer control systems should be expected provided that coordination for security and safety is not needed. Nowadays, a common protective relay IED can provide thousands of data and it is clear from this simple example that **data pre-processing** will be fundamental in Smart Grid. Information will be pre-processed and filtered by the IED so that only essential data will be sent to the DCC. Distribution Fault Anticipators and substation condition monitors are classical examples of data pre-processing.

Table 4-1: Choosing between centralised and decentralised distribution application as suggested in [15]

Criteria	Centralized	Substation Centred	Coordinated Hybrid Approach	Distributed
Number of Feeders	High percentage of automated feeders	All feeders downstream the substation are automated	Intermediate between Centralized and Decentralized	Small number of feeders geographically dispersed
Operator Visibility	Operator is informed about any action	Some control actions without operator notification are tolerated	Some control actions without operator validation are tolerated	Operator notification is mandatory, operator validation is optional
Availability of ICT	High speed wide area communication are necessary	Local area communication is needed	Mixed telecommunication infrastructure with medium/low speed	Local area communication is needed
Availability of Commercial	VAR/Volt optimization (VVO), FLISR, Optimal Network Reconfiguration (ONR)	FLISR, Distribution Fault Anticipator (DFA),	VVO, ONR, FLISR, Security Analysis (SA)	FLISR
Data Handling	Limited by data transfer capability	Suited for Waveform and EMC analysis	Some mechanisms for local data aggregation are necessary to limit data flows	Little or no capabilities

4.2.1 Central Control Systems

Power distribution control centres are responsible for day-to-day operation of distribution network to ensure power supply. The current level of automation in distribution networks is not high if compared to transmission systems. The Smart Grid is giving impetus to a next generation of sensors, actuators and control systems that will change profoundly the distribution control centres (DCC). Currently, the Operation Technology (OT) systems are used to deal with "faults", "outages" and day-by-day operation. SCADA, Distribution Management Systems (DMS), and Outage Management Systems (OMS) have been developed as stand-alone OT systems with little or no integration. The role of human operators is for this reason fundamental and interventions are necessary to correlate events and find a comprehensive solution. The time required for the decision-making process and the high dependence on the operator's capability to analyze data and find comprehensive solutions are the most significant shortcoming of current OT in DCC. The Operational Responsibility (OR) of DCC comprises maintaining and controlling the grid, and the load, fault and outage management.

The new generation of Smart Grid control centres must have interoperable OT-Information Technology (IT) systems and support systems. Languages like CIM (Common Information module), multi speak for Smart Grid as well as IEC 61850 standards have the objective to promote the interoperability of OT, IT and support systems. Indeed, the DNOs have SCADA, DMS, and IT systems such as Work Management Systems (WMS), Enterprise Assets

Management Systems (EAMS), AMI/MDM (Advanced Metering Infrastructure), DRPM (Demand Response Program Management), MWFM (Mobile Work Force Management), CIS (Customer Information System), etc. to manage their operations in control centres and back offices. The greatest novelty of the Smart Grid is represented by the integration of all these systems to perform better and faster data analytics for real-time data correlation, proactive and predictive actions, condition based monitoring, automate FILSR and the full involvement of DER, active demand and storage systems. The DCC operator will be empowered by the integrated and filtered information for timely and correct decisions in response to situations that require fast and correct decision in a more complex, integrated distribution system. Figure 4—1 shows the high level architecture of Smart Grid distribution control centre [16].

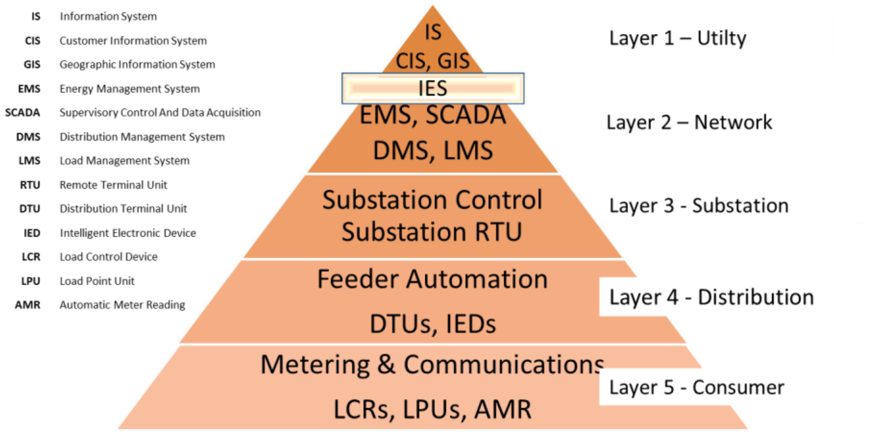


Figure 4—1: The high level architecture of a Smart Grid distribution control centre.

The integrated user interface of DCC will have GIS based maps for visualization of events and conditions. Dashboards and applications to monitor, control and manage the distribution network will be also available to the DSCC operator. The operator will not have to switch from SCADA for monitoring the network conditions, to OMS for reconfiguring the system, to DMS for running advanced optimization, and to MWFM for assigning crew to a specific work. The integrated single console will allow the operator to access all these systems with a unique interface. The Smart DSCC will have more responsibilities than in the past. As shown in Figure 4—2 a pyramid for the operator's hierarchy can be envisaged.

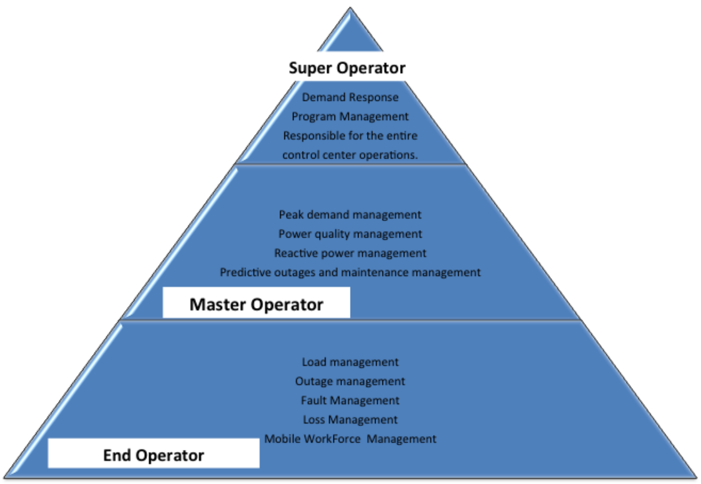


Figure 4—2: Hierarchy of responsibilities in future Smart Grid distribution control centre [17]

4.2.2 Distribution Management Systems (DMS)

A transmission/distribution network is a vertically integrated system and, therefore, a structure similar to that of Energy Management System (EMS) of transmission network is conceivable also for distribution networks. Although in common use, the term DMS is used today to mean solutions with very different complexity levels: from energy management (also with advanced functionality for off line studies of small entities) up to full real time management of the distribution network (including the underlying SCADA system). Distribution companies have always managed their networks according to four main interest targets (operation, maintenance, engineering, commercial management), which have influenced all the applicative functions of the DMSs and have often generated software applications independent of each other. The new trend is to design a single platform integrating all the functions and applications. However, depending on the main and prevailing target of the distribution company, the path leading to a complete integration of functions in the DMS might turn out to be different (Figure 4—3) .

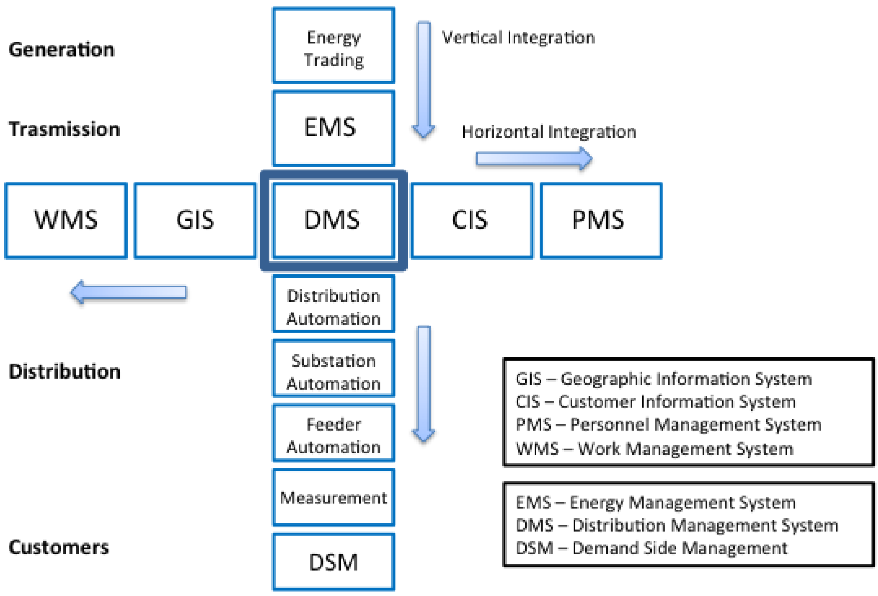


Figure 4—3: Vertical and Horizontal integration of a DMS

The development of distribution line and substation automation has led to the need, for control room operators, to have the information for managing the operation of the distribution network with a very high level of reliability as is usual in SCADA solutions and in typical transmission network functions, namely by adopting DMS-like structures. Solution a) "GIS-centric" therefore allows a more exhaustive representation of the network, but it requires a continuous alignment and synchronization of the database with the field data arriving to the SCADA. On the other hand, solution b) "SCADA-oriented", although less well performing in terms of distribution network visualization, allows a continuous alignment of network data and the possibility of developing more sophisticated control applications. The crucial element to the creation of a DMS structure is therefore the ability to interface with SCADAs and with the advanced functions available on the system, possibly developing systems that integrate the two approaches mentioned above. The functionalities of modern DMS can be divided into two different categories: basic functions and applications.

Basic functions are those that allow the integration with SCADA for maintaining and controlling the system. Supervisory control and Data Acquisition (SCADA), DCC operation and management (HMI), data handling and integration with field data and application functions fall in this category. Typically basic functions comprise data acquisition and storage in dynamic databases with all topological information. Basic functions generally allow the real time visualization of the network status with the interconnection of all components. SCADA functions supply real time monitoring and control of the distribution network by changing the regulators' set points, opening and closing switches, monitoring alarms and collecting measurements from the field.

The Application functions help operators to perform calculations, analysis and operation of the system and they can be divided into the three following categories:

a) Advanced Applications,
b) FLISR applications, and
c) Customer interface.

Among advanced applications, one can identify those allowing the management of the MV network; fault and security management; planning and load forecasting; and LV network management. In some cases there are functions for substation monitoring and control, and, with the increasing integration of distributed generation, for the involvement of generators in the optimal operation of the distribution system. With particular reference to the Smart Grid, the DMS will reproduce the typical EMS functions commonly used at transmission level, but the downshift of these technologies to distribution is neither straightforward nor easy due to the differences between transmission and distribution (e.g., the State Estimation). It is worth noting the application used by DONG Energy Distribution (Denmark) that combines NEPLAN power flow studies for state estimation and a SCADA system. An exemplary list of some available products for DMS/EMS applications as provided by the project SmartGen, a research project financially supported by *"Ricerca di Sistema*" (Research and Development Projects of general interest for the Electrical System) under the scheme set up by 8th March 2006 law [18], [19], can be found in [20].

The approach for DMS able to operate effectively on active distribution networks will therefore have to keep into account several elements, and make use of advanced communication technologies such as those recently introduced by IEC 61850 or IEC 61890.

From the analysis of these commercial products it can be argued that the majority of the DMS available in the market are SCADA based and still oriented to passive distribution systems but with the investments on Smart Grid programs DMS producers have been challenged to offer new products with EMS functions for off-line analysis and active distribution network operation. Interoperability and integration of the different subsystems is another important point for future products. The application of IEC standards (UML and XML) is important. Particularly, the IEC61970 allows the data exchange and integration of different products in a DCC with the use of CIM (IEC61970-301) for the representation of the system components. The majority of DMS are still designed with "ad hoc" solutions tailored for a specific distribution company and they require an adjunctive effort that can strongly influence and affect the final quality of the system. Applications functions such as state estimation, power flow analysis and optimization are not as standardized as SCADA. For this reason the producers often offer their experience and skills instead of a single product.

Central DMS for active distribution application have a general architecture as the one in Figure 4—4 [21]. The system aims at facilitating a high penetration of distributed generation and at exploiting the characteristics of the resources to increase the reliability and improve quality of service. The automatic optimization system for distributed resources is designed to be inserted in a structure shown in Figure 4—5 [21], [19] [18] [16], [22]. From the information detected with the measuring instruments an indication of the current operating conditions of the network (configuration and power flow) is obtained, while from the prediction blocks an estimation of the load and production of renewable sources plants is obtained, both for the next 24 hours and the next quarter of an hour. The daily optimization also takes into account the forecasted energy prices for the exchange with the rest of the electrical system.

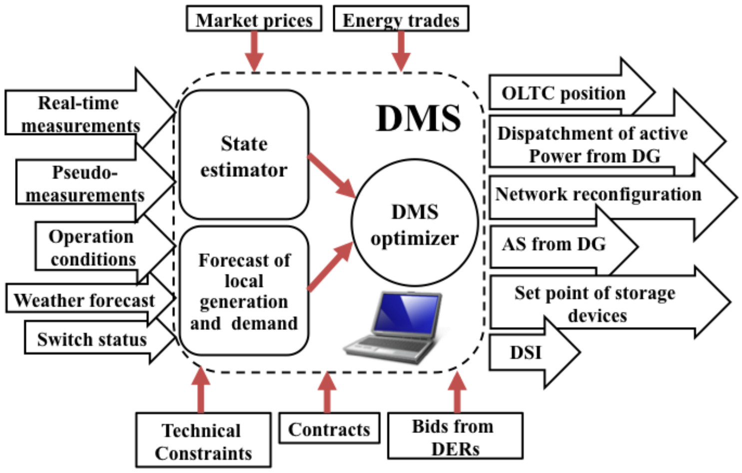


Figure 4—4 – Advanced DMS application architecture for the optimal active operation of distribution networks [21]

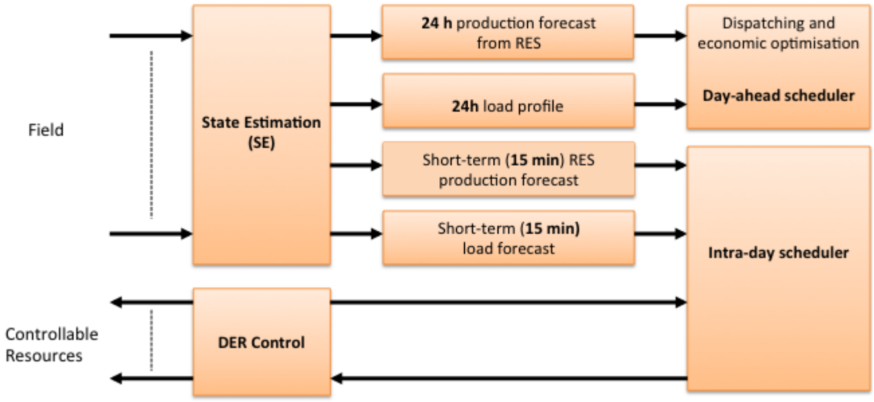


Figure 4—5 – The central DMS architecture proposed in [18]

The daily level of economic optimization supplies, for each quarter of an hour of the next day, the so-called economic dispatching; that is the indication of which controllable generation units must be kept in service and at what active power level, so as to minimize a target function based on the network operating costs. This information is sent to the second tier which, based on up-to-date short-term forecasts of the system status, performs a multi-objective optimization, where technical criteria for reliability and quality of service are also included, coordinating input levels of the active power with the other adjustment resources available on the network (reactive power and voltage adjustment).

4.2.3 Decentralized Control Systems

The majority of advanced control systems for Smart Grid applications are centralized or substation-centred, but research and demonstration projects are exploring capabilities and benefits of fully decentralized agents and a growth of peer-to-peer control systems should be expected provided that coordination for security and safety is not needed. Generally speaking, decentralised control systems can be less expensive and requires less communication infrastructures [23] [24] [25] [26].

The Multi Agent System (MAS) technology can offer numerous benefits in distributed power networks with characteristics of reactivity, pro-activeness, and social ability. Applications of MAS in power systems include disturbance diagnosis, restoration, protection, power flow and voltage control [27]. Several research projects have begun to investigate MAS as an approach to manage distributed generation, virtual power plants and micro grids [25], [28] The basic idea of agent-based active distribution networks is that inside the network, loads and generators interact with each other and the outside world. Although there is no strict definition about what an agent is, the literature provides some basic characteristics [26], [28]. The first characteristic is that an agent can be a physical entity that acts in the environment or a virtual one, i.e., with no physical existence. An agent is capable of acting in the environment, i.e., the agent changes its environment with its actions. Agents communicate with each other and this could be regarded as part of their capability for acting in the environment. This is a type of action because the environment is altered in a different way by this communication, rather than if the two agents were acting without any kind of coordination. Agents have a certain level of autonomy, which means that they can take decisions without a central controller or commander. To achieve this, they are driven by a set of tendencies. In addition, the autonomy of every agent is related to the resources that it possesses and uses. Another significant characteristic of the agents is that they have no, or only partial, representation of the environment. This is the core of the MAS technology, since the goal is to control a very complicated system with minimum data exchange and minimum computational demands. Finally, another significant characteristic is that an agent has certain behaviour and tends to satisfy certain objectives using its resources, skills and services. The way that the agent uses the resources, skills and services characterizes its behaviour. As a consequence, it is obvious that the behaviour of every agent is formed by its goals.

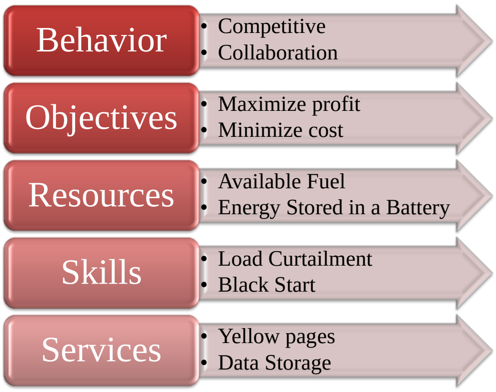


Figure 4—6: Behaviour, objectives, resources, skills and services of agents

MAS can be arranged to constitute a hierarchical control structure with local cells with the agents handling three functional aspects: management, coordination, and execution of actions of the active parties within the cells. For example, each secondary substation can be considered as a cell, managed by a moderator agent. The Low Voltage (LV) radial network supplied by a substation comprises loads, generators, and storage devices that can be represented and controlled by local agents. The communication between local agents, moderators and higher-level agents is based on a multi-agent platform (normally based on XML or UML protocols).

With MAS many common functions of Smart Grid operation can be simplified by reducing the need for massive communication data flow to a central processor (e.g., peer-to-peer communication). The DSE can be improved by using local measurements [23]. MAS can optimize voltage regulation and control; local agents detect a voltage issue and request to their neighbours support from DER, storage and controllable loads. Each involved agent analyses the situation and sends back a proposal with the most effective solution. A negotiation amongst agents allows finding the optimal local control. If this is not enough, moderators can negotiate with a supervisor agent a new set point for the On-Load Tap Changer (OLTC). Finally, MAS can be used for power routing to avoid congestions, minimize network losses, maximize the reliability of the transmission system, and maximize the serving of high-priority customers by using price signals.

4.2.4 Protection Systems

Smart Grids are based on three fundamental axioms:

- Availability of the measurements on the network
- Availability of a data communication network
- Availability of supervision and control systems

The availability of electrical measurements (voltage, current, active and reactive power) at major nodes of the network is essential to ensure a correct state estimation of the network. The measurements should be supplied in real-time to a supervisor system that controls the network. In this scenario, the protection system plays a key role. The protection system assures the correct selection of all faults occurring on the network. In the past, the distribution networks were built for passive customers and for that reason the protection systems were designed considering the electric power flowing only in one direction. The massive dispersed generation on the distribution network causes reverse power flows in both steady state and transient states, changing the paradigm for the development and management of the networks. The most recent systems use directional protection. There are two types of faults: phase-to-phase and phase-to-ground, both require directional protection. This means that all protection devices need the voltage reference to operate.

ANSI/IEEE C37.2 code 67 is a directional overcurrent protection. This protection is used to detect overloads and phase-to-phase faults. In this case the voltage phase is used as reference. For passive portions of the network, also the ANSI/IEEE C37.2 code 50 and 51, respectively a time zero overcurrent protection and a time overcurrent protection, can be used.

ANSI/IEEE C37.2 code 67N is a neutral directional overcurrent protection. This protection is used to detect phase-to-ground faults. In this case the reference is obtained by an open delta phase voltage connection.

In some applications the ANSI/IEE C37.2 code 21 distance relay can be also used. This protection evaluates the impedance by measuring voltage and current. Due to the short extension of some distribution lines, a communication link is necessary for the proper coordination with the other devices. Directional distance relays are the most effective protection devices but they are also extremely expensive in comparison with other relays currently used at distribution level.

A serious issue introduced by the current high penetration of DG is the so called "unintentional islanding". "Unintentional islanding" happens when a portion of the distribution network with a relevant Distributed Generation (DG) is disconnected by the rest of the network. In such case, voltage problems arise and frequency is not synchronous with the one in the transmission network. The probability to have an unwanted island is related to the amount of power generation connected to the distribution network and to the local loads. If there is a balance between dispersed production and load the unwanted island is very probable. Depending on the power flow conditions, there are two different levels for the unwanted islanding: the first level is at the MV feeder level, the second level is at the HV/MV substation level.

In order to avoid the unintentional islanding the protection system must operate very quickly by disconnecting the generators in a time shorter than the time of the first automatic reclose. For many reasons some sections of the network may be subjected to the risk of islanding: for example a network section can be disconnected due to a fault protection intervention. Each European country has defined a set of rules in order to achieve an adequate level of safety and reliability of the power system. In general the system must provide protection that avoids unwanted islands by disconnecting the generation units connected to the network portion of an island in as short a time as possible.

The common requirements are:

1. The DG must be disconnected if the voltage or the frequency are out of a contractual range
2. The DG must be disconnected if one or more phases of the prevailing network (transmission network) are missing
3. If there are automatic recloses, the DG must be disconnected before the first reclose

The anti-islanding protection assures all the requirements. There are three techniques to detect an unintentional island:

1. Passive protection
2. Active protection
3. Protection based on the communication network

4.2.4.1 Passive protection

The passive protection is a technique that uses a stand-alone digital relay installed in the generation plant. The relay is equipped by a set of standard protection functions that are:

- Under and over frequency protection function (ANSI/IEEE C37.2 code 81)
- Under and over voltage protection function (ANSI/IEEE C37.2 code 27 and 59)

To assure the anti-islanding protection, in addition to these protection functions there are various functions:

- Rate of Change of Frequency (ROCOF)
- Vector shift (jump)
- Inverse reactive power flux
- Inverse active power flux
- Rate of change of the active power

Under/over voltage/frequency protections

When there is a change in the network (a portion of the network with distributed generation is cut off), for the generation is like a load change and the electrical parameters (voltage and frequency) may change. This possibility depends on the unbalance between the load and the generation before the fault. If there is an unbalance, the under/over voltage or under/over frequency protections can operate.

Rate of Change of Frequency (ROCOF)

The deviation of the frequency from the rated system frequency indicates unbalance between the generated power and the load demand. If the available generation is large compared to the consumption by the load connected to the power system, then the system frequency is above the rated value. If the unbalance is large, then the frequency changes rapidly. In order to speed up the islanding decision, rate of change of frequency relay is used.

Vector shift

Due to the loss of the network contribution, the generator is called to vary its output to satisfy the energy balance. The change in power output from the generator causes the shift of the voltage vector. This protection is based on measuring the period of the voltage, which is compared with the previous measure. In island operation, the duration of the period, which is proportional to the phase, changes due to the unbalance between generation and load at the first opening. The relay phase shift is sensitive to disturbances such as faults on other feeders or transmission network transients and therefore it is difficult to coordinate with other protection.

Reverse reactive power flux

In case the power factor of the generation plant is equal to one (photovoltaic power generation), if a network section with DG is disconnected, there is a transient during which the generator provides reactive power to the network. The reverse reactive power flux protection is installed in the connection point between the distribution network and the generator.

Reverse active power flux

In some applications, the power generated is less than the load connected to the producer network. In this case a transient of active power that goes through the connection point between the producer network and the distribution network indicates a loss of network. The reverse active power flux protection is installed in the connection point between the distribution network and the producer network.

Rate of change of the active power

The monitoring of the active power can be used to detect the unwanted islanding. In fact a quickly change of the active power might be a signal of the loss of the upstream network. The rate of change of the active power protection is used in addition to the under/over voltage and under/over frequency.

4.2.4.2 Active protection

The active methods interact directly and continuously with the electrical system. Perturbations on the network are due to small variations of some electrical parameters by appropriate DG controls. If the DG operates in parallel with the network, the method generates small changes that are not sufficient to trigger the relay, whereas in case of loss of the network the changes become significant and the DG is disconnected.

The most common active protection functions to avoid the islanding are:

- Reactive power export error
- Fault level measurement
- System impedance monitoring

Reactive power export error

This relay interacts with the regulation system forcing the generator to provide a level of reactive power that can be maintained only if the transmission network is connected. The operation occurs when there is a difference between the exported reactive power and the reference value for longer than a settable time. To avoid unwanted tripping in case of fluctuations of the source, the set interval is chosen greater than the duration of possible fluctuations.

Fault level measurement

The fault level in a certain point of the grid can be measured using a point-on-wave switched thyristor. The thyristors are controlled to be activated close to the voltage zero crossing, and the current through a shunt inductor is measured. The system impedance and the fault level can be quickly calculated (every half cycle) with the disadvantage of slight voltage shape changes near the zero crossover.

System impedance monitoring

It is a method that detects the system impedance with active monitoring. A high frequency source (a few volts at few kHz frequencies) is connected via a coupling capacitor to the interconnection point. The capacitor is in series with the equivalent network impedance. When the systems are synchronized, the parallel impedance Z_{DG} and $Z_{Network}$ is low; therefore the HF-ripple at coupling point is negligible. After islanding, the impedance increases dramatically to Z_{DG} and the divided HF-signal is clearly detectable.

4.2.4.3 Protection based on the communication network

Recently a new approach is used to manage the system protection on Smart Grids. The major nodes are connected by a communication link. Via this link the devices interact in order, for example, to disconnect a DG from the primary substation.

Comparison of rate of change of frequency protection (COROCOF)

If there is a communication network, the technique called COROCOF can be used. The method is based on the comparison of frequency change rates in two or more points of the network. The method is able to discriminate the frequency variations due to loss of network from the other changes due to other causes. A lock signal is transmitted by the transmitter relay to all relays located near the DG. The transmitter relay transmits this signal if the frequency change is generated by events not related to the loss of network.

4.2.5 Customer Control (Load/Generation)

From the operation standpoint, real-time monitoring and control capabilities provided by the Smart Grid lead to new active operation of distribution feeders such as volt/VAR optimization or new network topologies performance optimization. Better data provides opportunities for improved network performance analysis. Moreover, new market structures might influence operation and control of the distribution network and lead to new customer behaviours regarding both power consumption and local power production. This needs to be undertaken in the context of the uncertainties that result from the integration of high levels of intermittent generation from Renewable Energy Sources (RES), and optimized use of any stored energy. In fact, if used for peak shaving or load levelling to compensate the sudden power variations caused by RES generators, Demand Side Integration (DSI) programs and Distribution Energy Devices (DES) might reduce the variance of the RES production and become a viable alternative to network reinforcement (i.e., no-network solutions in planning). Demand Side Integration (DSI), Energy Efficiency (EE), and Time-Of-Use (TOU) rate scenarios will affect system peaks. Different Distributed Generation (DG), Distributed Storage (DS), Plug-in Electric Vehicle (PEV) and heat pump/electric boilers penetration scenarios will impact on system demand. Uncertainties on data concerning PEV penetration, battery charging typologies and drivers' habits make it difficult to foresee and to estimate PEV impact on electric distribution networks. Several possibilities can be envisaged for load contribution in system management and control as pointed out by a series of international initiatives [29], [30], [29], [31]. The following list is quite exhaustive.

- ***Cost Reduction***. A key driver for demand management is cost avoidance and reduction. This is particularly significant during peak demand periods featuring price spikes: during such periods, even a limited demand reduction can determine a major price reduction. For instance, load management can be highly valuable during peak price periods, where a limited reduction in load consumption (5%) may bring notable price reduction (up to 50%). Demand response can also save all customers' money indirectly by reducing wholesale market prices and mitigating price volatility.
- ***Market Efficiency***. When customers receive price signals and incentives, usage becomes more aligned with costs. To the extent customers alter behaviour and reduce or shift on-peak usage and costs to off-peak periods, the result is a more efficient use of the electric system***.***
- ***Customer Service***. Many customers welcome opportunities to manage loads as a way to save on energy bills and for other reasons such as improving the environment.
- ***Market Power Mitigation***. DR (Demand Response) programs help to mitigate market power (i.e. the abuse of a dominant market position) of traditional and new energy suppliers. This is especially the case when DR can occur essentially coincident (i.e., in near real time) with tight supplies and/or transmission constraints that might lead to market power.
- ***Risk Management***. Energy retailers purchase power in wholesale markets where prices can vary dramatically from day to day, and hour to hour. They can use demand response to substantially reduce their risk and their customers' risk in the market.
- ***Environmental.*** *Demand Response* (DR) can help reduce environmental burdens placed on the air, land and water by reducing the need to operate polluting plants. DR can also reduce or defer new plant development, and transmission and distribution capacity enhancements resulting in land use benefits for neighbourhoods and country-sides.

- ***System Security and Reliability***. Customer demand management can enhance security and reliability of the electric system by providing reductions in use during emergency conditions or preventing system degradation into them. When security aspects are of major concern, the concepts and use of Interruptible Loads and of Curtailable Loads are becoming widely adopted.
- ***Interruptible Loads*** (IL). ILs have been used by utilities for decades, essentially with the goal of enhancing reliability. In exchange for the possibility of being shed in case of necessity by the system operator, ILs pay for their energy at a lower price. Characteristics of interruptible load programs usually are:
    a) Large load reductions of at least 1 MW and usually including the entire facility;
    b) Short notification to comply such as just an hour and as short as ten minutes;
    c) Interruption could be required at any time of the day or day of the year;
    d) Mandatory compliance with failure to perform resulting in huge penalties;
    e) Max number of interruptions allowed during any year;
    f) Permanent discounts on electric bills.

  ILs are usually large industrial customers whose main production cost is the electric power needed for the production process and who could interrupt or time-shift operations for a few hours: such customers obviously look for savings on the power bill, and thus, in order to pay energy at a lower price, they are willing to accept the chance of being interrupted.
- ***Curtailable Loads*** (CL). CLs imply a "milder" approach than ILs: the requirements for the participants are in fact less strict than for IL programs. Characteristics of CL usually are:
    a) Smaller load reductions expected such as 100 to 200 kW minimum, but as high as 500 kW or 1,000 kW to qualify;
    b) Fewer number of curtailment requests such as 15 times in the year;
    c) Curtailment requests only during certain days and times, such as weekdays and between 11 a.m. and 7 p.m.;
    d) Mandatory participation once an agreement has been reached;
    e) Small penalties for failures to meet load reduction targets;
    f) Credits based on amount of load reduced and applied against standard tariffs.
- ***Active user.*** An active user is the so-called *prosumer* as a user intended to be able to have a bidirectional exchange with the DNO. The *prosumer* can sell its flexibility to the energy market in order to provide services and support to the distribution network. This market dynamics is called Active Demand. A user modifies his own consumption/production profile in order to respond to a price signal. To improve the performance of the load and local power generation model two elements have to be considered:
    1) Level of participation of the *prosumer*: one of most difficult aspects related to active demand is the ability to forecast the real participation of a user. The acceptance model is necessary because every user is willing to modify the consumption profile in different ways. This depends on price signal, but also on available flexibility, willingness to reduce the comfort, etc.
    2) Payback effect: this is the reaction of the user when the active demand request finishes. In particular these aspects can play a fundamental role in direct control of thermostatic loads, where the DSO can play with the switching on/off of some particular loads to manage for instance RES integration.

Many projects are exploring the role and the potential of active users in modern distribution networks. ADDRESS is one of the most advanced and biggest since it aims at involving a large number of real customers in Spain, France, and Italy [32]; similar projects are on-going in Europe and USA [33], [34]. From these projects it appears that a new subject, the Aggregator, will be essential to involve active users in DSI and to allow the interaction with the DNO/DSO. The Aggregator allows active users to participate in power and services market by finding a good compromise between the DSO needs and the elasticity and flexibility of the active users involved (Figure 4—7).

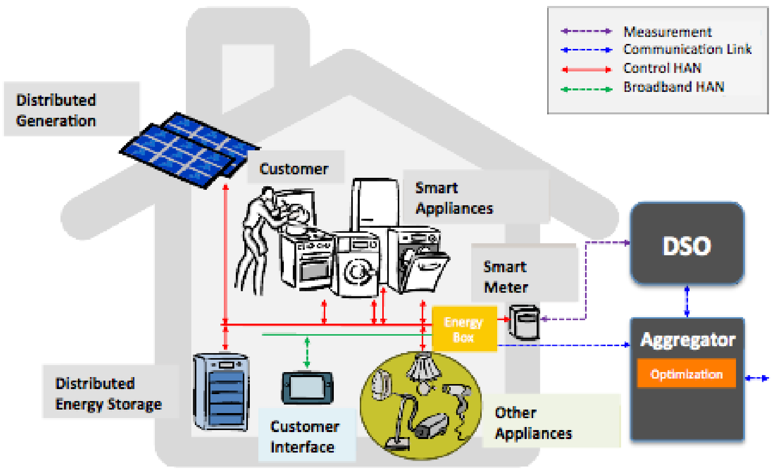


Figure 4—7: General architecture for Active Demand (courtesy of ATLANTIDE, a research project financially supported by *"Ricerca di Sistema"* (Research and Development Projects of general interest for the Electrical System) under the scheme set up by 8th March 2006 law)

Electrical appliances are fundamental to involve active users in DSI since they represent a significant part of the loads that can be involved in DSI policies (Figure 4—8). According to ADDRESS, but similar approaches can find in other projects, the active consumer can be involved with Smart Electrical Appliances and Smart plugs. Smart plugs allow not-intelligent appliances to get involved in active demand. The Aggregator sendS signals to Smart Appliances (e.g., washing and dishing machines, home refrigerators, electrical heating systems, electric heat pumps, etc.) and Smart Plugs through a gateway connected to the intelligent metering system (e.g., the so-called ENERGY BOX in ADDRESS) or through a standard internet TCP-IP gateway with home EMS functions. The ENERGY BOX (or the gateway) is the interface between the customer and the Aggregator (that is to say the interface between the customer and the DNO/DSO). All smart loads, but also generators and storage devices if they exist, communicate with the smart box and react to signals related to market prices as well as network operation. The Smart Appliances have high efficiency and communicate with the gateway to follow operational policies required by the DSO, even though the customers can always override any signal from the network, or by the home EMS. With these functionalities the Smart Appliances and those connected to the Smart Plugs can offer load shifting – to make home consumption homothetic with renewable generation if it exists – and load shedding to follow Volume Peak signals, Power Peak signals and Price signals.

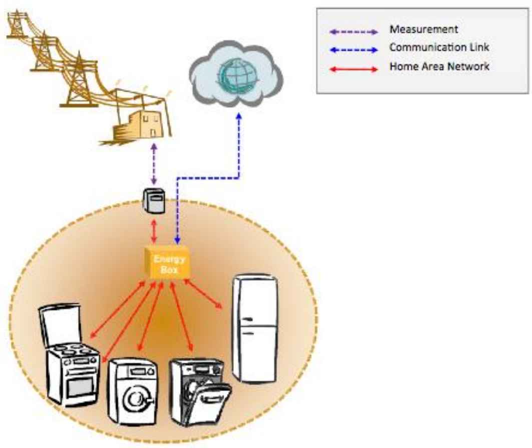


Figure 4—8: Active Demand according to ADDRESS and ATLANTIDE projects.

Finally, large scale adoption of the electric vehicle (EV) paradigm raises the interest of many stakeholders and will change the way customers can interact with the grid. Currently, the automotive industry is focused on EV manufacture while governments and policy makers underline the potential of environmental benefits and job opportunities creation [35], [36]. The electricity sector is evaluating foreseen impacts on their infrastructures to serve an additional electrical load, in this case with special characteristics compared to the common ones. Four different EV charging schemes are considered:

1. *Dumb Charging at peak hours*: Electric vehicles of the same type are considered to charge at the same time, during peak hours.

2. *Multiple tariff policy aiming charging at Valley Hours*: Electric vehicles of the same type are considered to charge at the same time, during off-peak hours. This type of recharging is used to simulate the target of a multiple tariff policy. It could be obtained with new appropriate Multi-Tariff incentive schemes, and with technological solutions such as smart meters and timers in the cars.

3. *Smart Charging*: Electric vehicles are charged selecting the starting charging hour to “fill the valley” of the overall aggregated profile, considering demand and distributed generation. Local issues were not taken into account to design this type of charging, so it only fills the valley from an aggregated point of view. This recharging system is expected to require controls system and communication systems.

4. *Smart Charging/de-charging:* The electric vehicles acts as a controllable load or as a generator in the power systems with high penetration of renewable energy sources, depending on the actual load and power generation condition in the network. They are in this way used to minimize peak-consumption and to “fill the valley”.

A massive deployment of electric vehicles will require significant changes in power system operation procedures and practices. Some of the main effects associated to high EV penetration in LV grids can be: increase of power losses, overloading of lines and cables, poor voltage profiles, and voltage and load imbalances. The magnitude of the EV impacts on distribution networks is influenced by several factors, such as the EV integration level, the EV owners’ behaviour, mobility patterns, the network load profiles and technical characteristics, the number and location of fast charging stations in the grid, and the EV charging modes, amongst others.

4.2.6 Grid Control

The term “Grid Control” is very wide and describes all the actions taken by DSO to guarantee security and reliability of the distribution systems. Centralized and decentralized systems have been deployed in distribution systems in recent years mainly focused on the automation of FLISR to reduce the impact of faults to customers. It is worth noticing that in many countries DNO/DSOs are regulated subjects with incomes that are also performance based and not only asset based; and this was the reason that moved DSOs to increase the level of automation in their networks.

The Smart Grid paradigm is changing the meaning of the term “Grid Control” since DSO, according to the relevant regulatory framework, are going to deploy true operation systems in their distribution networks to solve operational issues (Table 4-2) [37]. This is something completely new in the distribution system where the operational issues were solved at the planning stage by designing networks capable to cope with the possible worst scenarios and no, or few, operation controls were necessary apart from FLISR. Modern centralized and decentralized SCADA control centres with DMS/EMS capabilities described in section 4.2 give the opportunity of a real-time network control that can increase the security of the system, but also can improve the quality of service and reduce capital and operational costs. Indeed, the Smart Grid allows DSO to add flexibility and intelligence to the network through the use of automatic switches for optimal reconfiguration, adaptive protection systems for integration of DER, power electronics-based controllers to increase reliability as described in section 4.2.4. In the context of grid control, the role of Distribution Fault Anticipators (DFA) will increase the reliability of Smart Grids by offering proactive actions to DNO/DSO [34], [15]. DFA technology implements information from sensitive monitoring to detect subtle electrical precursors that anticipate an impending failure of line apparatus.

Other controls will make the distribution system more similar to the transmission one. An example is represented by the voltage and VAR control that is not a new concept, but nowadays, the efforts to improve efficiency, reduce demand and achieve better asset utilization are giving a new and higher importance to Volt/VAR optimization. In fact, with the new Smart Grid functionalities, DER and storage can be fully involved in this classical activity of DNO that essentially means keeping the voltage acceptable at all points along the feeder and maintaining a high power factor.

Table 4-2: Common issues of distribution systems with high DER and RES shares. Classical and smart no-network solutions compared [37].

Technical Issue	Network solutions	No-network smart solutions
Voltage rise	Reinforcement Operational power factor 0.95 lagging Generation tripping	Volt/VAR control Storage Generation Curtailment On-line reconfiguration
Voltage drop	Reinforcement Fixed capacitor banks	Volt/VAR control Storage Demand Side Response On-line reconfiguration
Network Capacity	Reinforcement	Storage Generation Curtailment Demand Side Response On-line reconfiguration
Network Power Factor	Limits / bands for demand and generation	Storage Unity power factor generation
Sources of Reactive Power	Transmission network Fixed capacitor banks	Storage SVC Volt/VAR control
Network asset loss of life	Strict network designs specifications based on technical and economic analyses	Dynamic protection settings Asset condition monitoring

The broader objectives of volt/VAR control and optimization in a smart distribution system can be achieved by adding communication facilities to connect existing controllers with the processors located in substations and control centres or adding decentralized intelligence to DER. Many existing volt/VAR controllers are equipped with communication facilities that support industry standards such as IEC 61850. Small generators, often connected through inverters, do not always have such capabilities because for long time they had no or few involvement in network control. Nowadays, TSO and Regulators started to oblige small and micro generators to participate in volt/VAR regulation by imposing stringent requirements on the characteristics of power converters with novel grid codes and even the smallest LV power producers will have controllers for volt/VAR optimization and DSO/DNO will deploy volt/VAR control systems that provide coordinated control of all volt/VAR control devices [38]. There are three main solutions to the system-level approach to volt/VAR control and optimization:

- **SCADA "rule-based" solution:** Appropriate volt/VAR control actions are taken by applying a predetermined set of rules to the measured quantities. This approach is straightforward, easy to understand, and fully leverages existing equipment. The drawback is that it network reconfiguration cannot be easily implemented and RES intermittent production cannot be easily followed.
- **"Model -based" solution:** Advanced distribution management systems (DMSs) may include an optimal power flow solution that operates on a dynamic model of the distribution system. The volt/VAR control can be more easily applied to frequently reconfigured network. This system is more complex and expensive than the previous one.
- **Adaptive solutions:** This category of volt/VAR control and optimization solutions learns over time what control actions to take based on real-time measurements of electrical operating conditions, ambient weather conditions, past experience under the same conditions and distribution state estimation. A major advantage of this approach is that it does not require the utility to maintain an as-operated system model

and is thus a highly scalable solution. The adaptive solution requires a processor that can be installed in a substation or control centre location.

4.3 Communication Technologies

The Smart Grid's field area network presents a unique niche in the field of telecommunications. 6 technology options are approaches for being the most popular technologies, chosen so far, for FAN deployments:

1. **PLC (Power Line Carrier)**: There are a range of different PLC technologies and protocols – in this case we consider 'narrowband PLC', a set of technologies that can achieve bit rates of around 2-150kbps, on medium and low voltage networks;
2. **BPL (Broadband Power Line)**: In the beginning, BPL was touted as a solution for broadband internet in homes and offices. Today, there are limited live deployments of BPL for internet service, but Smart Grid represents a relevant niche that could offer growth opportunities;
3. **Private Wireless (RF – Radio Frequency)**: Network technology with the most traction in the US today, provided by a number of Smart Grid specialists including Aclara, Elster, Itron, Landis+Gyr, Silver Spring Networks and Trilliant;
4. **Public Wireless (LTE/3G/GSM/GPRS)**: The third most popular option for Smart Grid FAN in recent years – those operated by mobile carriers such as AT&T and Verizon in the US, or Vodafone and Deutsche Telekom in Europe;
5. **WiMax**: Communications standard for 4G telecommunications networks, similar to LTE. Telecoms carriers have begun deploying 4G networks globally in recent years. LTE is expected to gain a larger market share over the next few years.
6. **Fibre Optics**: A powerful communication technology based on optical fibre cables with a very high bandwidth and very low latencies. Building up a fibre optical network is related to costly infrastructure investments, however, more and more fibre optical networks are deployed, primarily for internet usage but also for FAN deployments.

The IEC 62357 Reference Architecture gives an overview of the useful standards in the domain of interoperability for power utilities:

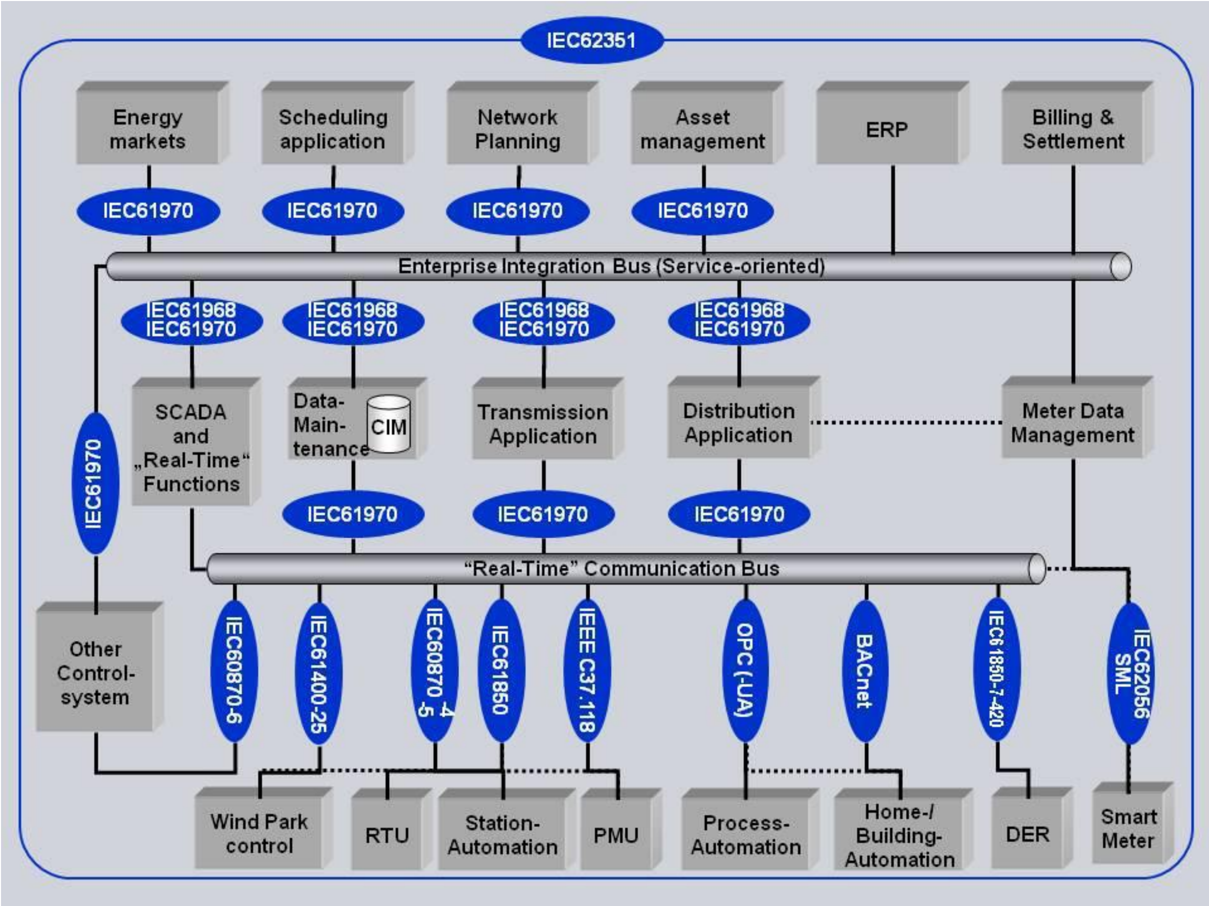


Figure 4—9: overview of the useful standards in the domain of interoperability for power utilities

4.3.1 PLC (Power Line Carrier)

Power line carrier communication designates a technology which uses LV and MV electrical lines for telecommunication services. The usage of power line carriers in non-dedicated communication channels has been standardized in two main application modes, narrowband and broadband. The narrow band PLC provides lower data rate and long distance communications as a result of the lower frequencies and bandwidths. Broadband PLC focuses on high data rate and short distance communications for Internet and Multimedia based services.

In this case we consider 'narrowband PLC', a set of technologies that can achieve bit rates of around 2-150kbps, on medium and low voltage networks, and therefore they are slow and unreliable for critical infrastructure needs.

PLC technologies use the electrical wires themselves to carry data, thus avoiding the need to build costly new network infrastructure. Therefore, PLC technologies have some natural advantages:

- **Network ownership**: the responsibility for building and running a Smart Grid network falls on the same utility that owns the physical infrastructure;
- **Grid topology**: the communication network and grid infrastructure are one and the same;
- **Fault detection**: Analysis over how devices are performing and in what configuration;

Additionally, PLC networks can provide information that will ultimately be able to feed into geographical information systems and PLC devices can also form a 'mesh', that is, PLC nodes connected can repeat signals to and from each other, and in cases where the distribution grid forms a mesh.

Smart Grid PLC deployments in Europe have been adopting narrow band low bit rate PLC which use CENELEC A frequency bands from 3 KHz to 95 KHz reserved for electricity suppliers. Figure 4—10 depicts the frequency bands defined by CENELEC EN 50065-1 and the use case scenarios. However, this frequency band brings difficulties on overcoming noise (noisy environments – roads where passing motors can introduce noise, or a town square where a fountain's mechanisms disrupted communications);

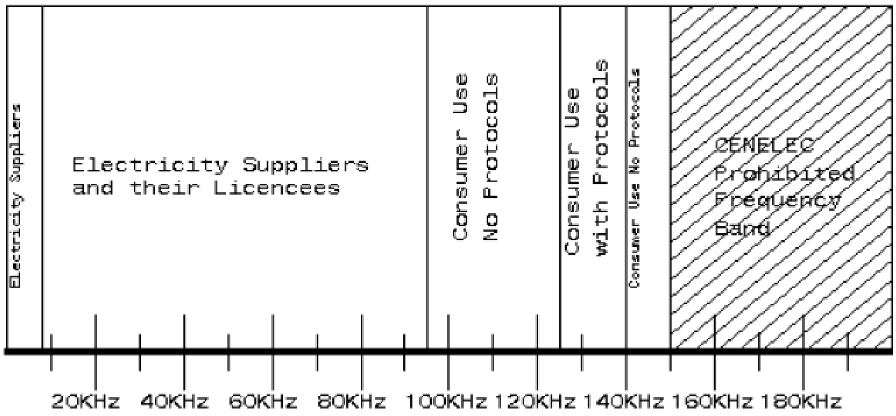


Figure 4—10: Frequency band allocation for PLC networks in Europe

In order to carry the digital information over wired power lines, PLC communication devices perform modulation operations in order to convert digital information towards frequency signals carried as electromagnetic waves over the wire. As a result from different modulation techniques, five main PLC technologies are being deployed in the field.

4.3.1.1 PLC – G3

PLC G3 technology, specified in [39], is the communication technology being developed by ERDF in France which aims to be interoperable with previous PLC SFSK EDF deployments. The last mile PLC G3 technology aims to provide communications between smart meters and concentrators which transfer data towards the Automatic Metering Management (AMM). The overall architecture considers meters, the PLC LAN, concentrators/hubs, the WAN and Central System components. The central system interacts through the WAN telecommunication network with all the hubs deployed in substations or secondary substations. Hubs mediate communications between central system and meters by collecting data from meters using the PLC G3 communication technology over the LV network.

PLC G3 technology, implemented by MAXIM semiconductors, adopts the OFDM technique which divides the CENELEC A band bandwidth into 36 orthogonal independent communication sub channels. Each sub channel performs the digital modulation DBPSK or DQPSK allowing a maximum data rate of 33.4 kbps and a maximum MAC service data unit of 235 bytes. The OFDM based specification of PLC G3 addresses the main objectives of providing a highly reliable and robust communication channel with a minimum data rate of 20 kbps in a reduced CENELEC A band fraction from 35.9 KHz to 90.6 KHz. Although based on the usage of a OFDM system, which provides advanced coding techniques against impulsive noise and interferences, PLC G3 modems perform link adaptation by measuring the quality of the received signal and deciding the modulation schemes to be used. Additionally, the system is able to differentiate OFDM sub-channels with bad SNR and avoid transmitting data through them.

In the MAC layer specification [40], [41], PLC G3 adopts an IEEE 802.15.4 based medium access control which reuses in PLC networks functionalities available from low power and low data rate wireless personal area networks (WPAN). The MAC specification provides network based functionalities (neighbour discovery, network join, network coordination by WPAN coordinators, bootstrapping mechanism, route discovery and path discovery), security functionalities (EAP authentication, authentication, key distribution, group key distribution and AES 128 bit MAC data ciphering) and access control functionalities (beacons, frame acknowledge, frame retransmission, frame segmentation and reassembly, synchronization, collision detection and channel access).

The MAC layer medium access control implements the Carrier Sense Multiple Access with Collision Avoidance (CSMA/CA) channel access method which considers random, back-off and inter-frame times. Additionally the CSMA/CA in PLC G3 implements priority contention windows which will benefit real time or control applications deliver messages as soon as possible.

4.3.1.2 PLC – Prime

The PoweRline Intelligent Metering Evolution (PRIME) alliance group [42], responsible for the specification of PLC PRIME technology [43], coordinated by Iberdrola has as alliance principal members meter manufactures (Itron, Ziv and Landys + Gyr), semiconductor manufactures (ADD, Texas Instruments, ST) and software developers (Current Group). The PLC – PRIME technology is deployed in Spanish STAR pilot project. Figure 4—11 depicts the reference architecture of PLC PRIME technology which is composed by PLC meters, data concentrators and the utility hosting billing and management services. Between the Data concentrator and smart meters, the PLC PRIME technology provides a Local Area Network based in the electrical power lines. The reference architecture considers an Internet based broadband area network for communications between data concentrators and utility hosts and is suitable for Automated Metering Management (AMM) applications.

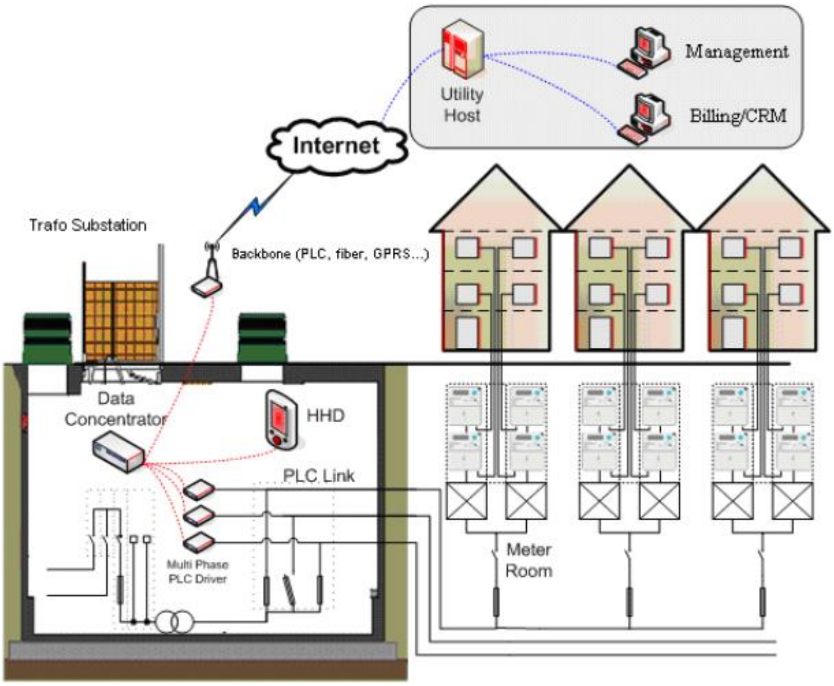


Figure 4—11: PLC Prime reference architecture

The PRIME alliance focused on providing a low cost and very robust communication network with a data rate of tens of kilobit/s. In the physical layer, OFDM technique was chosen due to its robustness against impulsive noise, its high spectral efficiency and its adaptability against interferences in presence of frequency selective channels. The physical OFDM based layer specified for PLC PRIME comprises CENELEC A band and, in result of well-known bad performance in frequencies below 40 KHz, the frequency range covers the interval from 41.992 kHz to 88.867 kHz with a bandwidth of 47.363 kHz located on the high CENELEC A band.

The OFDM signal use 97 equally spaced sub carriers and which will differential modulation schemes for transmitting the digital data in the analogue PLC carrier. Three possible modulation schemes, DBPSK, DQPSK and D8PSK allow non-coded speeds of 47, 94 and 141kbit/s. In the case of D8PSK modulation, PLC PRIME allows a maximum data rate of 128.6 kb/s and a maximum 2268 bytes MAC service data unit.

In the physical layer, the PLC PRIME specifies:

1. physical data plane:
   Data plane primitives allow MAC layer to request sending data in the physical channel (*request*), physical layer to confirm the request primitive (*confirm*) and physical layer to send received data towards the MAC layer (*indication*).
2. Control data plane:
   The PLC PRIME specifies control data plane primitives for setting or reading Automatic Gain Control, timers, carrier detection, noise level, signal to noise ratio, last received frame quality and zero cross time values.
3. Management data plane:
   Physical management primitives are invoked to reset all internal state and clear queued received or transmitted data (*reset*), complete any pending action and suspend its activities (*sleep*), resume its suspended activities (*resume*), enter into non default operation modes (*test mode*) and query information about given PRIME information base attribute (*get*).

PRIME information base attributes allow reading statistics from the physical layer such as AGC values, processing delays (Rx and Tx), queue lengths, dropped counters and CRC incorrect frames.

In the MAC layer, PLC PRIME specifies sub-network concept as a tree with two types of nodes. The Base node acts as master and provides connectivity by managing resources, register operations and connections. Service nodes are either leaves (terminal) or branch points (switch) of the tree. Both service nodes have the responsibility of performing registration operation for connecting to the sub-network and switch base nodes have the additional responsibility of forwarding neighbours' data to propagate connectivity in the PLC medium. Figure 4—12 depicts a PLC PRIME tree composed by two levels and a combination of all different allowed nodes.

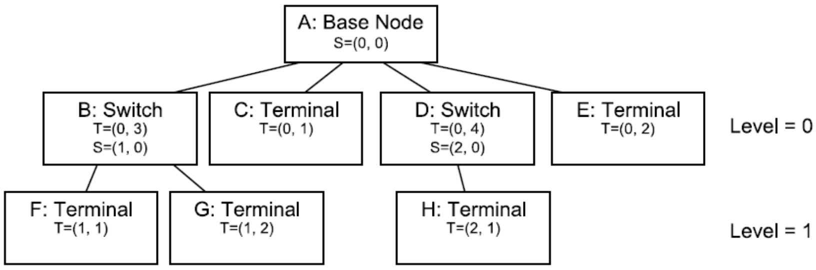


Figure 4—12: PLC PRIME tree example

The PLC PRIME MAC layer follows the IEEE 802-2001 addressing where each device has a 48 bit MAC address assigned during manufacturing process. In order to reduce addressing length, the MAC layer supports an addressing structure which is composed by the sub-network address (identifies the sub network address by its base node 48 bit MAC address), switch node identifier (8 bit identifier of each switch node inside a sub-network), local node identifier (14 bit identifier assigned in the registration process) and local connection identifier (9 bit identifier for a specific connection).

Additional MAC layer functions include starting and maintaining sub-networks, channel access, tracking service nodes, packet switching (unicast, broadcast and multicast), security and encryption, direct connection establishment and release and packet aggregation, acknowledge and retransmission. MAC channel access adopts the CSMA-CA algorithm which considers back-off timers, priority levels and contention periods.

Concerning security, the PLC PRIME specification considers two main profiles. Security profile 0 is used when communications don't require privacy, authentication and data integrity. Security profile 1 fulfils all privacy, authentication and data integrity based in 128-bit AES encryption. Security framework considers key distribution and management performed by key derivation techniques where working keys (initial working, working and sub-network working keys) are derived from device parameters (master key, device secrete key, key diversifier, unique secrete key and unique identifier).

PLC PRIME protocol stack, depicted in Figure 4—13, considers convergence layers for an encapsulation of networking and application layer data units over PLC MAC. PLC PRIME specifies the IPv4 convergence layer and the IEC 61334-4-32 convergence layer.

IPv4 convergence layer provides a connection-oriented path for transferring IPv4 packets over the PRIME network. Base node acts as an IP router between backbone and PRIME subnets. All nodes can either be assigned a statically IPv4 address or obtain IPv4 address from DHCP. Optionally TCP and IPv4 headers may be compressed after negotiation during the connection establishment phase.

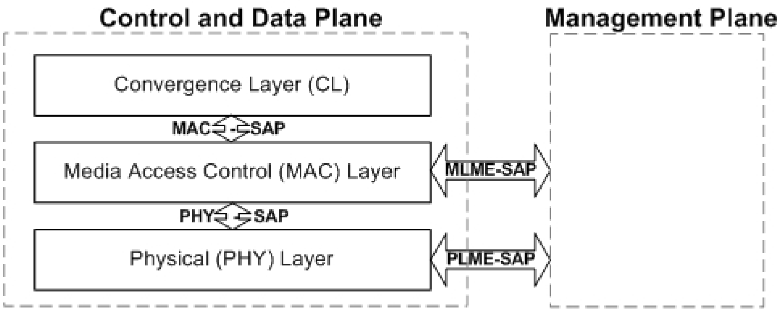


Figure 4—13: PLC PRIME lower layers protocol stack

The IEC 61334-4-32/LLC convergence layer provides services to map LLC connection-less protocol to the connection oriented PRIME MAC. Initial connections must be initiated by a service node and, once the session is established, base node initiates all data transfers within the session. This profile allows applications that use IEC 61334-4-32 LLC based services to exchange data over PRIME MAC medium.

4.3.1.3 PLC – OSGP

The PLC OSGP (Open Smart Grid Protocol), specified by ESNA (Energy Services Network Association) [44], is deployed in Smart Grid projects and pilot projects in Europe at Denmark, Netherlands, Russia, Sweden, Finland, Germany and Austria. Echelon [45], one of the board members of ESNA and developer of smart meters, develops the Networked Energy Service system depicted in Figure 4—14 for advanced metering applications. NES System architecture considers two main networks, an IP based and PLC based network. The IP based wide area network allows communications between data concentrators and utility hosts while the PLC OSGP local area network provides interaction between data concentrators and smart meters.

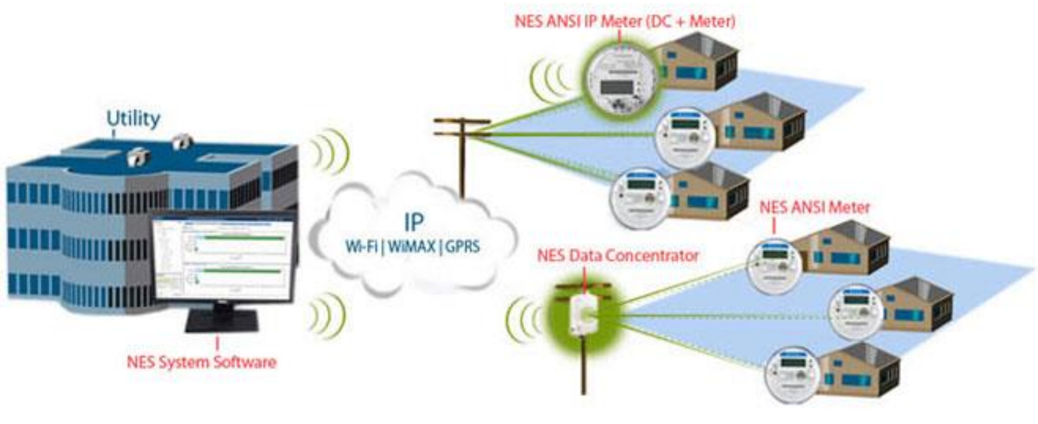


Figure 4—14: Network Energy Service system architecture

PLC OSGP technology is based in European Building Automation EN 14908 standard and provides a 5 kbit/s bit rate. The EN 14908 standard derives from the LonTalk protocol adopted in the LonWorks Echelon technology.

Table 4-3 overviews the protocol stack for PLC OSGP. In the physical, data-link, network and transport layers, the specifications are based in EN 14908 building automation standards, while in the application layer, the OSGP protocol is based in IEEE 1377.

Table 4-3: PLC OSGP protocol stack

Layer	Protocol	Based in
Application	OSGP	IEEE 1377
Transport **Network** **Data Link**	PLC OSGP	ISO/IEC 14908.1
Physical	PLC OSGP	ISO/IEC 14908.3

Open Smart Grid protocol initiative from ESNA pretends to deploy additional functions in smart meters beyond Automatic Meter Reading functionalities such as power quality monitoring and urgent alarm notification.

4.3.1.4 PLC – DCSK

The PLC DCSK technology, developed and patented by Yitran [46] and Renesas, is deployed in the InovGrid pilot project in Portugal and in Endesa in Spain. Differential code shift keying (DCSK) [47] is considered by its developers as the most robust PLC technology. PLC DCSK adopts the spread spectrum technique where the result signal has a bandwidth considerably larger than the original information. As a sequence of the spread spectrum mechanism, the signal level may be lower than the noise level which provides less susceptibility against high narrowband noise, spectral distortion and burst noise and a communication technique with higher security and reliability.

For the spread spectrum mechanism, Yitran patented a spread spectrum technique [48] based in the DCSK modulation, which performs cyclic shifting of the basic symbol (chirp wave form) in the transmitter. The cyclic shifting mechanism requires a detection of the shift to be performed at the receiver. Figure 4—15 depicts a generic example of how a cyclic shifting system was performed at symbol 8. In the example, all the symbols used to map digital data from 0 to 6 will be used to map digital data from 9 to 15 when cyclic shift is performed. Before the shift, data from 7 to 15 will be used to map digital data from 0 to 8. By performing cyclic shifting, digital input data will never use same symbol and will never be affected by the same channel noise.

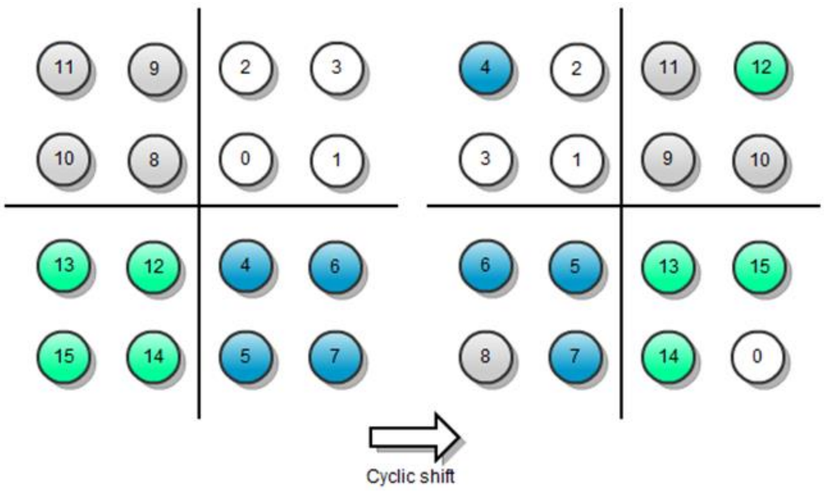


Figure 4—15: DCSK Cyclic Shifting sample performed at symbol 8

The chirp wave form is used to replace the pseudo-random PN sequence in the direct sequence spread spectrum DSSS system. In the DCSK modulation, the information data is translated into analogue waves which are then multiplied in the DSSS system.

PLC DCSK technology supports different transport modes in the CENELEC band, a robust mode (2.5 kbit/s) and extremely robust mode (0.625 kbit/s). Lower data rates are achieved due to the split of CENELEC band into three transmission bands from 18-44 kHz, 38-63 kHz and 58-89 kHz. The same waveform is repeated in the previous three transmission bands which provide an extreme robust modulation and higher availability in noisy environments.

New developments of this technology achieve 150Kbps in CENELEC-A, and is compatible with older versions. In the Yitran PLC technology, the data link / medium access control layer [49] is performed with a patented adaptive back off CSMA/CA based in IEEE 802.11 optimized for the power line medium. Other functionalities of DLL / MAC layer are adaptive rate control to channel quality, acknowledge and unacknowledged services, network diagnostic and analysis and automatic rate control for all physical transport modes.

In the Portuguese pilot project InovGrid, EDP Distribuição deployed 30k EBs - EDP Boxes (project denomination for smart meters) using mostly PLC DCSK technology for communications towards 340 DTCs – Distribution transformer Controller (project denomination for data concentrators) deployed in secondary substations. The pilot project had as main objectives implementation of a smart city covering all consumers, providing EDP experience for future roll-out and evaluating the impact the benefits of Smart Grids brought to consumers and network operation.

Besides smart metering, the pilot project focused on advanced automation and sensing functionalities secondary substation such as Low Voltage sensing, automation of Medium Voltage cells, power transformer sensing and remote control of public Street Lighting. InovGrid architecture, depicted in Figure 4—16, considered two main systems to exchange data with DTCs deployed across Évora municipality. The Advanced Meter Reading system covered metering and billing objectives while the Supervisory Control and Data Acquisition (SCADA) system was designed to provide advanced functionalities in the Low Voltage grid.

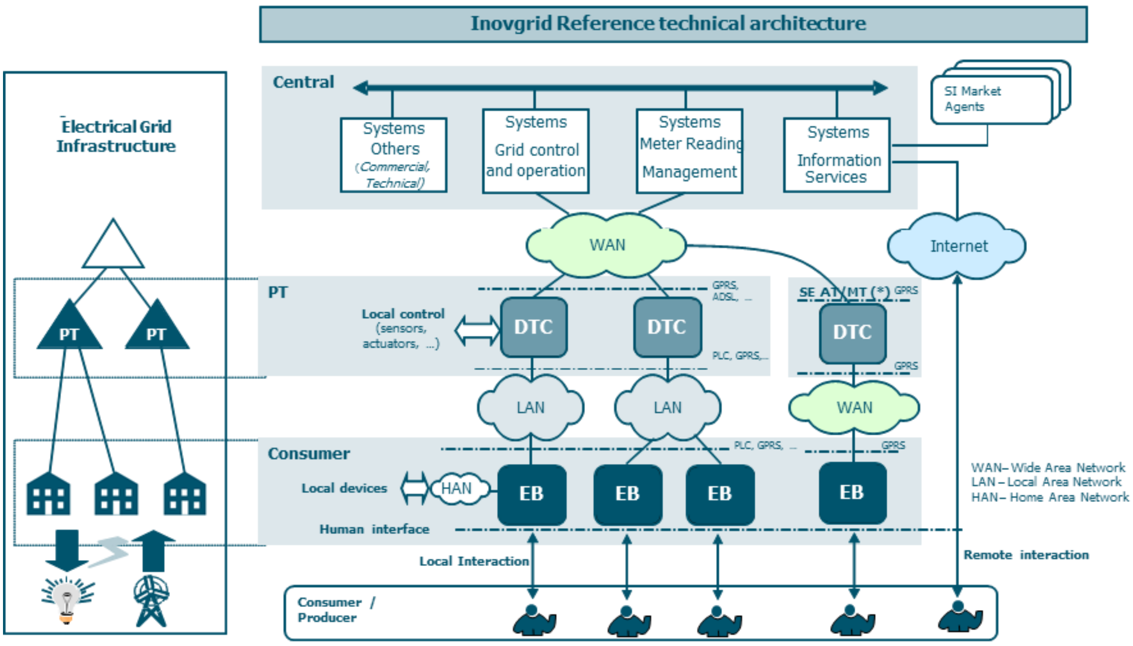


Figure 4—16: InovGrid pilot-project reference architecture

Beside the AMR and SCADA systems interaction with DTCs through the Wide Area Network GPRS connection provided by a service provider, such systems exchange technical information within Geographical Information, Asset Management and Outage Management Systems allowing EDP to maximize data availability within different technical and commercial systems under operation.

4.3.1.5 IEEE P1901.2

IEEE P1901.2 [50], [51] is a standard which specifies communications for narrowband PLC devices adopting frequencies until 500 KHz. The standard defines an indoor and outdoor communication technique over low voltage lines up to 1000V, through MV to LV transformers up to 72kV both in rural and urban grids. IEEE P1901.2 also considers multi-kilometer long distance communications in rural applications. The standards has as main objectives addressing grid to meter, electric vehicle to charging station, home area network, lighting and solar panel applications.

Concerning the physical and medium access control layers, this standard specifies mechanisms for balancing the usage of PLC channels classes and coexistence between different narrow bands low frequency band devices. Previous mechanisms also assure coexistence with broadband power line communications by minimizing emissions in frequencies greater than 500kHz and assure desired bandwidth delivery. The technology will provide scalable data rates below 500 Kbps and will support IPv6 internet addressing.

Physical layer of IEEE P1901.2 is bases in orthogonal frequency division multiplexing (OFDM) technique and defines as mandatory DBPSK, DQPSK and D8PSK modulation techniques and considers interoperable profiles with PLC G3 and PLC PRIME in CENELEC A band.

The Medium access control layer is based in IEEE 802.15.4 carrier sense multiple access mode with collision avoidance implementing advanced features such as routing, mesh and quality of service. Concerning security and privacy, IEEE P1901.2 assures the necessary requirements allowing the usage for sensitive services and by defining access control, confidentiality, integrity, anti-replay and denial of service prevention functions. During the authentication phase, this standard adopts EAP authentication which supports several authentication methods (such as password based and certificate based).

This standard defines either the physical and medium access layer in concordance with Open System Interconnection (OSI) reference model.

4.3.1.6 PLC S-FSK / IEC 61334

The PLC S-FSK / IEC 61334, adopted by ERDF consortium as Linky PLC [52] and by ENEL as SITRED [53], is a communication technology being deployed by Itron, Landys+Gyr and Iskraemeco in the cities of “Lyon” and “Tours” Smart Grid pilot projects. ERDF Linky architecture, depicted in Figure 4—17, considers communications from Linky smart meters to Linky data concentrators (PLC S-FSK) and between Linky data concentrator and ERDF hosts (wide area network).

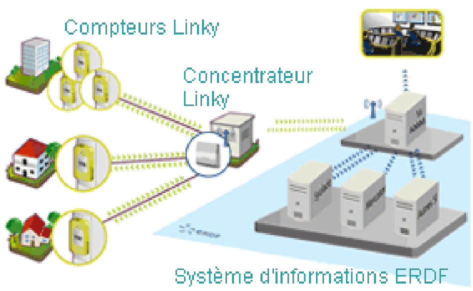


Figure 4—17: ERDF Linky system architecture

In the PLC S-FSK physical layer [54], [55], the spread-frequency shift keying S-FSK modulation combines advantages from spread spectrum systems and adopting conventional and low cost FSK modulation. Difference between Conventional FSK and spread FSK lies in the frequencies for the data ‘0’ and ‘1’ being spread far from each other.

The S-FSK transmitter assigns a space frequency to 'data 0' and a mark frequency to 'data 1'. Figure 4—18 depicts the frequency spectrum resulting from a S-FSK system considering a noise level higher at sample frequency ($N_{fs} > N_{fm}$).

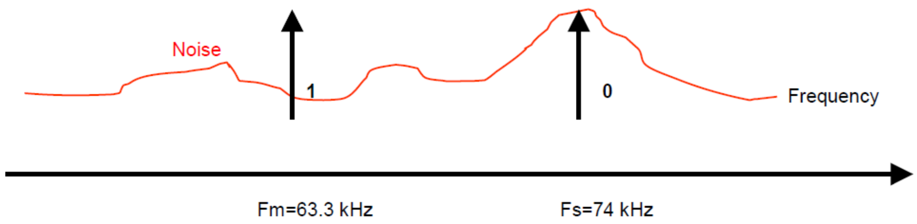


Figure 4—18: Spread-frequency shift keying frequency spectrum

The receiver performs conventional FSK demodulation and measures signal to noise ratio at both frequencies. Based on reception quality and a defined threshold, the receiver will select a communication frequency channel and ignore the other. For the scenario depicted in Figure 4—18, the receiver will select frequency mark where the signal to noise ratio is higher. This modulation allows data to be transmitted even when one of the frequency channels is completely hidden. Over the selected channel the amplitude shift keying ASK modulation converts digital data into analogue waves to be carried over the selected frequency.

The PLC S-FSK link layer is split into a MAC and LLC layers. For the MAC layer, all communication modules are assigned with a MAC address by the concentrator which has its own MAC address. The assignment is performed during the discovery phase and the addressing must be assigned in an ascending order starting from one. The MAC layer also includes functionalities for group based addressing (broadcast and multicast communications), synchronization, frame repetition and sub-frame transmission. The LLC layer follows the IEC 61334-4-32 specification.

In the application layers, ERDF adopts the DLMS application layer while ENEL specified the proprietary application protocol SITRED.

4.3.2 BPL (Broadband Power Line)

Utilities are still learning with Broadband Power Line (BPL) technology. There are limited live deployments, but Smart Grid represents a relevant niche that could offer growth opportunities.

BPL nodes can also be arranged in a mesh because BPL networks have such high bandwidth that their endpoints are not single devices, instead they use 'gateways' that link to more than one meter or sensor. BPL gateways communicate with multiple meters and devices trough a secondary technology, such as Zigbee or wireless M-bus (a meter reading standard). BPL can act as a bridging technology between field area and wide area networks.

BPL bit rates are far beyond what PLC or wireless mesh can provide (greater capacity for adding devices on the network, and adding additional functionality besides electric metering). BPL is best suited to urban environments with densely spaced devices, related to a vendor's opinion.

On the other hand, there are issues related with interference and a lack of reliability (very few vendors have successfully made BPL work in the past) and it´s widely acknowledged to be more expensive than other options.

BPL typically uses spectrum between 1MHz and 50 MHz. Thus it claims to achieve bit rates around 1-5Mbps, or up to 15Mbps on a MV line. This far outstrips the 1-2kbps available on old narrowband PLC technologies, or >100kbps for newer protocols such as PRIME. On the other hand, these high frequencies result in shorter communication distances/line length. BPL can also improve reliability, thanks to a larger number of available frequency channels (980 as compared to 96 for PRIME). This gives a data packet more option when certain frequencies are disturbed by interference.

4.3.3 Private Wireless (RF – Radio Frequency)

Network technology with the most traction in the US today, provided by a number of Smart Grid specialists including Aclara, Elster, Itron, Landis+Gyr, Silver Spring Networks, CISCO and Trilliant.

Private Wireless use the 900MHz or 2,4GHz bands (or other licensed spectrum) which are arranged in a 'star' or a 'mesh' topology, being that the former is more popular. Private Wireless solutions are less susceptible to noise (interference) than power line carrier-based technologies, as well as being more reliable and faster.

Star topologies allow easy hand-offs for mobile endpoints, and is suited to higher bandwidth applications

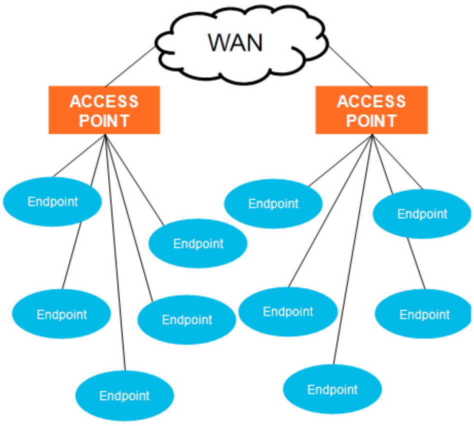


Figure 4—19: Star topology

On the other hand, Mesh topologies were developed to improve reliability and offer redundancy through the availability of multiple paths, also Mesh networks may be better suited for distributed control compared to star-based wireless or public cellular networks. Mesh solutions typically include automatic discovery and dynamic signal routing, setting up the network is relatively simple.

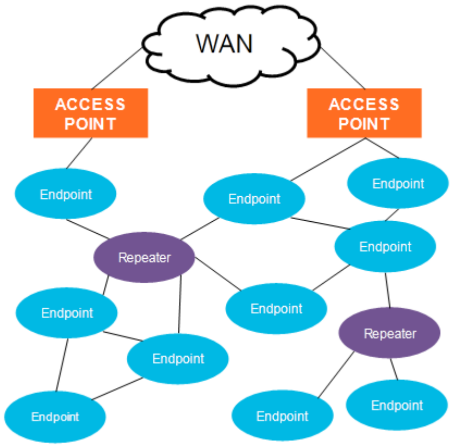


Figure 4—20: Mesh topology

Private wireless networks can overcome several disadvantages related to public networks efficiency and quality of service, for example the difficulty of penetrating thick building walls, especially in underground metering rooms in high-rise buildings. As result for a better performance, utilities will have to support the management, deployment and operation of the network and support the expensive fees for renting radio spectrum licenses like in Europe where it's not permitted to operate on unlicensed spectrum in the 900 MHz band (GSM) and limitations on antenna power come into play (10mW).

This kind of technology permits the coexistence of metering and automation, with some network engineering, like we can see in the next example of a trial in EDP Portugal:

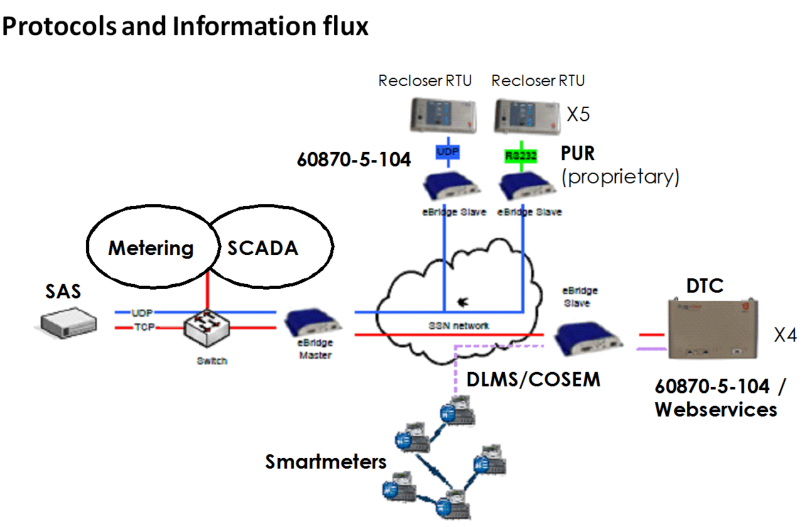


Figure 4—21: Trial in EDP Portugal

4.3.3.1 RF Mesh from Silver Spring Network

RF Mesh owned by Silver Spring Networks [56] is a proprietary wireless communication technology which explores mesh networking. Silver Spring Networks provides advance and all-IP based networks for Smart Grid solutions, from data centre to customers/homes. Figure 4—22 depicts the RF mesh based networking solution offered by Silver Spring Networks. RF Mesh solution, beside smart meter communication modules, requires the existence of access points and optional relays and bridges.

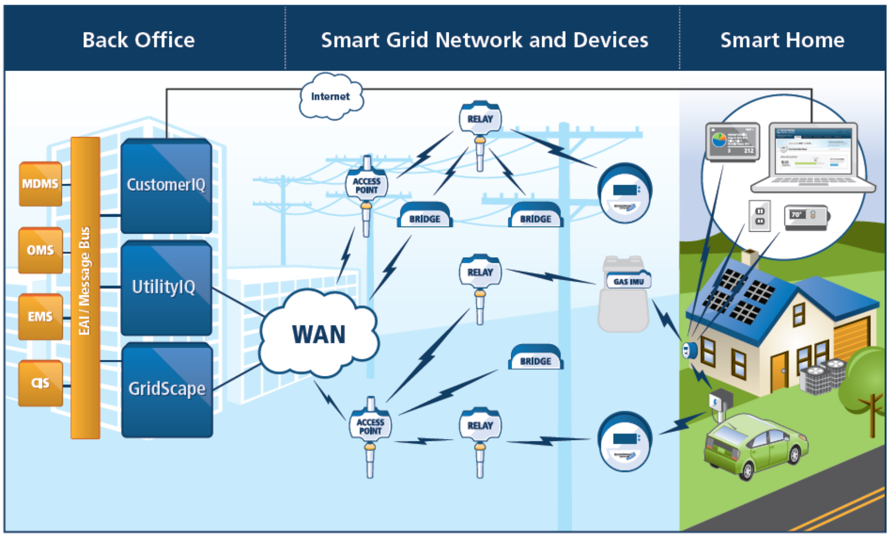


Figure 4—22: RF Mesh Smart Grid architecture

Silver Spring Networks develops the communication modules for the Landys+Gyr and secure electricity meters, forming a highly resilient mesh network for the utility. In the physical layer, RF Mesh adopts the frequency hopping spread spectrum (FHSS) technique where the carrier frequency periodically jumps between predefined channels. The channel list for RF-Mesh is listed in Table 4-4 [57].

Table 4-4: RF Mesh channels

Channel Number	Channel Frequency (MHz)	Transmit Local Oscillation (MHz)	Receive Local Oscillation (MHz)
0	902.7584	782.3360	792.1664
1	903.7824	783.3600	793.1904
2	904.8064	784.3840	794.2144
3	905.8304	785.4080	795.2384
4	906.8544	786.4320	796.2624
5	907.8784	787.4560	797.2864
6	908.9024	788.4800	798.3104
7	910.1312	789.7088	799.5392
8	911.1552	790.7328	800.5632
9	912.1792	791.7568	801.5872
10	913.2032	792.7808	802.6112
11	914.2272	793.8048	803.6352
12	915.2512	794.8288	804.6592
13	916.2752	795.8528	805.6832
14	917.2992	796.8768	806.7072
15	918.3232	797.9008	807.7312
16	919.9616	799.5392	809.3696
17	920.9856	800.5632	810.3936
18	922.0096	801.5872	811.4176
19	923.2384	802.8160	812.6464
20	924.2624	803.8400	813.6704
21	925.2864	804.8640	814.6944
22	926.3104	805.8880	815.7184
23	927.3344	806.9120	816.7424

In the 902-928 MHz band, RF Mesh modules [58] provide 100 kbit/s data rates using a transmitter power between 500mW to 1W. Since the selected frequency band is license-exempt in United States, RF Mesh MAC layer implements functionalities for robust security and encryption, dynamic network discovery and self-healing, continuous neighbour monitoring and route calculation.

4.3.4 Public Wireless (LTE/3G/GSM/GPRS)

The third most popular option for Smart Grid FAN in recent years are public wireless networks – those operated by mobile carriers such as AT&T and Verizon in the US, or Vodafone and Deutsche Telekom in Europe.

In Public Wireless the gateway is essentially a radio with a communications card (SIM card) which can talk to local cell towers via GPRS or other protocols. Carriers have kept a fairly low profile in the Smart Grid world.

Public wireless networks do not require the grid operator to own, manage or operate the wireless network and leasing an existing public network may be cheaper and easier for the utility. Commercial carriers are able to spread the cost of building, maintaining and upgrading networks amongst many customers, whereas private networks are paid for solely by the utility. Utilities using public networks are not committed to stay with the same level of performance for the long term, and will be able to add more functionality in future.

On the other hand, public wireless networks typically don't reach the entire locations where utility devices are located, so a minimum of additional communications infrastructure is needed. Telecom operators tend to perform periodic upgrades in the communication system, which may be costly if utility is required to replace or upgrade communication modules. Also public wireless networks are also known as best-effort networks where latencies cannot be guaranteed and a poor reliability is achieved as experienced by many consumers through dropped calls, particularly in urban areas. Utilities remain reluctant to rely on third party carriers for critical applications such as outage management.

The General Packet Radio Service (GPRS) [59] is a wireless communication technology which uses the 2nd generation GSM circuit switched network for the establishment of packet based communications. The GPRS/EDGE radio access network is based in a time division multiple access system where mobile devices share communication timeslots. Each radio frequency carries a TDMA frame which can be shared by eight mobile devices. In order to support packet and circuit services, the mobile network operator (MNO) needs to deploy an infrastructure depicted in Figure 4—23.

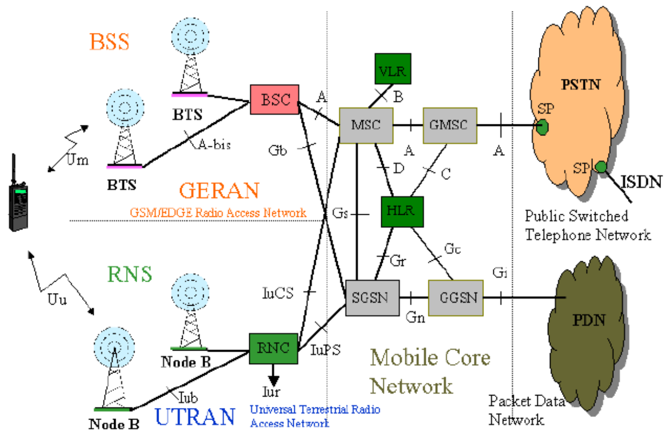


Figure 4—23: Mobile network operator infrastructure

In the radio access networks, MNOs are deploying different radio access technologies using the same mobile core network. The GSM based radio access network is deployed with base transceiver stations (BTS) and base station controllers (BSC). BTSs are responsible for functions such as creation and management of the radio cell while BSCs perform functions such as handover support (between BTS under the same BSC) and interaction between GERAN and the MNO core. In Europe governments allocate the 800, 900, 1800 and 1900 MHz licensed frequencies for MNO 2nd generation technology.

For GPRS communications, each device can allocate up to 5 timeslots in the TDMA frame. A maximum 80 kbit/s data rate is achieved using 4 time slots for downlink and a 20 kbit/s is achieved using 1 time slot for uplink. Table 4-5 overviews the downlink and uplink data rates and the number of TDMA time slots required for the different GERAN transmission modes.

So far several utilities have been testing the usage of wireless carriers. MNOs such as Vodafone in the UK and Germany, T-Systems in Germany, Optimus in Portugal, Telenor in Scandinavia and AT&T and Verizon in the US have acted as carriers for Smart Grid communications. In Europe, GPRS technology is mainly used for communications between data concentrators and utility servers in the wide area network interface of a Smart Grid. Additionally several smart meter manufacturers, such as Itron and Landys+Gir, are selling smart meters with GPRS communication modules. Utilities are deploying this meters in very low population density and rural areas.

Table 4-5: 2G/2.5G GSM data rates and services

Transmission mode	Down-link [kbps]	Up-link [kbps]	Number of slots (DL/UL)
CSD	9.6	9.6	1 / 1
HSCSD	28.8	14.4	2 / 1
HSCSD	43.2	14.4	3 / 1
GPRS	80.0	20.0	4 / 1
GPRS	60.0	40.0	3 / 2
EDGE	236.8	59.2	4 / 1
EDGE	177.6	118.4	3 / 2

In order to provide higher data rates for mobile users, 3GPP (3rd Generation Partnership Project) has been specifying physical radio access networks based on the previous 2nd generation core network. Between the specified RANs, the UMTS radio access (UTRAN) is a technology based in the spread spectrum code division multiple access system where all mobile devices share the same spectrum and several devices are allowed to send data simultaneously. In less populated and rural areas, deployment of 3G networks is still far behind 2G. Governmental entities are allocating 2100 MHz International Mobile Telecommunications band for MNOs to provide UMTS services.

3GPP is involved in the specification of LTE (Long Term Evolution), a radio access technology which aims to provide higher data rates, best quality of service and lower latencies. Also known as 4G, LTE is suitable for a mass-market usage of any type of IP-based services.

So far the wireless carriers have kept a fairly low profile in the Smart Grid world and none has pushed hard for market share in this space. Most of today's Smart Grid deployments that use cellular in the field area network are based on GPRS, a '2.5G' technology, though 3G is increasingly widespread. Table 4-6 shows the relative performance of major cellular technologies.

Table 4-6: Performance of major cellular technologies

	2,5G (GPRS)	**2,75G (e.g. EDGE)**	**3G (e.g. HSPA+)**	**4G (e.g. LTE advance)**
Maximum (nominal) download bit rates	56 kbps	180 kbps	56 Mbps	1 Gbps
Maximum (nominal) upload bit rates	40 kbps	120 kbps	22 Mbps	500 Mbps

4.3.5 WiMAX

WiMAX (Worldwide Interoperability for Microwave Access) [60] is a communication standard for 4G communication networks such as LTE. Based on IEEE 802.16 standard, it provides data rates up to 72 Mbit/s supporting different network topologies and several transmission modes and bandwidths to adapt to propagation conditions and user demands.

WiMAX systems can provide 30-40Mbps maximum bit rates, but future updates are expected to rise that to 1Gbps. With sufficient bandwidth to transport data to and from hundreds of endpoint devices, they are often used as 'trunk' communication links.

WiMAX offers much greater bandwidth than narrowband PLC and mesh networks and it can also be used to build private networks (no need to rely on a public carrier) to link up smart meters and concentrators. This deployment of a dedicated network for Smart Grid applications cannot be justified if utility needs to support license fees. In areas where public services are available, WiMAX may be a solution. Most pilot projects are being performed in the United States and Australia using radios from Alcatel-Lucent, AirSpan and GE Energy (e.g. GE is running smart metering projects in Michigan and Texas).

WiMAX are high performance networks for more data-intensive or critical applications, such as real-time grid automation and demand management allowing utilities to be more flexible in adding more applications and devices to the network in future, as investments in grid monitoring and automation follow.

On the other hand, most in the telecoms world believe that LTE will ultimately 'win out' as the technology of choice for public wireless carriers. Telecoms carriers have begun deploying 4G networks globally in recent years and it's expected to gain a larger market share over the next few years.

In the physical layer, WiMAX adopts a scalable OFDM scheme which supports bandwidths from 1.25 MHz to 20 MHz, multiple antenna support (MIMO techniques), adaption to propagation conditions through BPSK, QPSK, 16-QAM or 64-QAM modulations and frequency division duplex (FDD) and time division duplex (TDD) access modes.

WiMAX technology is applicable for point-to-point line-of-sight (LOS) communication links up to 50 km using directional antennas and for non-line-of-sight (NLOS) broadband coverage which typically achieves few kilometres with omni-directional antennas.

The spectrum allocation for WiMAX communication networks it's not globally harmonized. Governmental entities in Europe are considering the attribution of 500 to 800 MHz licensed frequencies for 4th generation technologies but waiting the release of licenses from analogue TV carriers. A licensed band is already being used by operators between 2.3 to 4.0 GHz and, in some countries, unlicensed bands are available between 5.0 to 5.8 GHz. Table 4-7 overviews the foreseen frequency ranges being considered for this technology.

Table 4-7: Frequency ranges foreseen for WiMAX

Frequency range	Usage	Remarks
500 – 800 MHz	licensed	Under consideration in Europe and elsewhere, but awaiting roll-out of digital/mobile TV
2.3 GHz – 4.0 GHz	licensed	Several frequency chunks already in use by licensed operators or use under consideration
5.0 – 5.8 GHz	unlicensed	Mainly for back-hauling

4.3.6 Range of Communication Technologies

Table 4-8 presents an overview of the communication technologies described in sections 4.3.1 to 4.3.5.

Table 4-8: Overview and range of communication technologies

	PLC	BPL	Wireless/ RF	GPRS	WiMAX
Nominal bit rates	2-130kbps	5-15Mbps	100-400 kbps	56kbps	30-40Mbps
Typical endpoints per access point	Dependent on grid – as many as 800 endpoints per transformer	Each gateway can handle many endpoints depending on environment (e.g. 5 to 10)	5000	N/A	N/A
Topology	Mesh or Star	Mesh or Star	Mesh or Star	Public networks	Public or private networks
Technology strengths	Uses existing infrastructure; provides information about physical grid	Uses existing infrastructure; high bandwidth; can add applications in future	Easily configured; low opex;	Low capex; no need or utility to own and operate network	High bandwidth technology available today; can add applications in future
Technology barriers	Some PLC standards lack bandwidth; interference issues;	Potential higher cost in comparison to PLC and private wireless	Underground / dense building environments are challenging; requires licensed spectrum or available unlicensed spectrum; higher capex than public wireless	High opex; potential need for future upgrades; perceived unsuitable for grid automation; incomplete signal coverage	Relatively few providers in Smart Grid space; likely to be superseded by LTE; higher cost;

Performance in deployments	Enel Telegestor smart metering project: bimonthly reading of all 32k meters. Daily reachability (meter read within 24h of request; attempts each 35mins): 99,9% Reachability index (successful attempts/ total attempts in 1 year): 98,5%	Power Plus E.ON Westfalen MV automation pilot: Achieved an average bandwidth of 13 Mbps with 24ms latency using BPL technology on 20kV line	Silver Spring Networks project for AEP Ohio: AMI:99,98% availability; 7 sec average time for on-demands reads. DA: 99,9% packet success; average response time 600ms. (Typical 15ms per 'hop'; 1-10 hops per packet)	Smart metering projects in Europe and North America. SmartSynch as claimed latencies in order of 100ms and costs in the range of 'pennies' per device per month	N/A

The range of communications techniques is identified based on the applicability scenario. The local area network represents the last mile connectivity between secondary substations and house meters. In Table 4-9 is shown the overview and range of communication for PLC technologies.

Table 4-9: Overview and range of communication for PLC technologies

Technology	Range	Topology	Max bit rate	Considerations
PLC G3	LAN	Mesh	33.4 kbit/s	Developed by ERDF / France; Compatible with PLC S-FSK;
PLC Prime	LAN	Mesh	128 kbit/s	Developed by Iberdrola; Pilot project in Spain;
PLC OSGP	LAN	Mesh	5 kbit/s	Developed by ESNA; Pilot projects in Denmark, Netherlands, Russia, Sweden, Finland, Germany and Austria;
PLC DCSK	LAN	Star	2.5 kbit/s	Patented by Yitran; Pilot project in EDP / Portugal;
PLC S-FSK	LAN	Star	2.4 kbit/s	IEC 61334; Pilot projects in ERDF France (Linky PLC) and ENEL / Italy (SITRED PLC);

Although some utility players remain cautious on public wireless (particularly in the US, which favours the 'own and operate' network model), it's probable that public wireless will continue to win AMI projects, and the carriers will become more active in Smart Grid. Hybrid networks involving cellular in conjunction with mesh or PLC could be the system of choice for AMI projects in topographically diverse service areas.

Utilities have shown themselves willing to alter technology choices after pilot projects; for this reason existing technology choices for pilot projects do not necessarily presage the final decision for commercial roll-outs. There are a large number of pilots going on in European countries for which this could be the outcome.

4.3.7 Security considerations for a Smart Grid

The Smart Grid can be described as a distributed system resulting from different components which are connected to provide the so called smartness to the power grid. With its implementation, the amount of critical information travelling between the field components and the IT infrastructure increases greatly which reflects the inevitability for utilities to start investing in cyber security as they invest on systems or telecommunications. This investment is critical to provide a robust, secure and effective infrastructure capable of handling the variety of equipment, protocols, processes and data flow resulting from the Smart Grid technology.

The Smart Grid represents an increased appliance of digital information and advanced technologies which also come with the risks of exposing the control network to different and new threats attached to these technologies. Therefore, cyber security and the compliance with its standard requirements is a priority to maintain or even increase the reliability, safety and efficiency in the Smart Grid.

The additional risks introduced by the existence of a Smart Grid include:

- Introduction of common vulnerabilities in interconnected networks;
- Susceptibility to the introduction of computer viruses on the network;
- Potential failures in the protection of sensitive information such as customer data.

The communication technologies are one of the main vectors for the Smart Grid operation. The amount of information flowing between the different components must be delivered, and most of all, delivered safely. The sensitivity of the data flowing inside the Smart Grid such as metering information, the control and telemetry data, alarming information and other, is undeniable.

The Smart Grid communication includes a diverse set of layered protocols and physical media. The information travelling across these networks may be exposed to different types of threats and eavesdropping, forgery and manipulation. However, utilities are now relying on cyber security and the mechanisms available to prevent such devious acts and protect the information inside the Smart Grid.

Even when considering the increase on the grid exposure to threats, there are security mechanisms that can and should be applied to guarantee the following security properties, ensuring that the Smart Grid communications are protected and dependable.

- **Confidentiality** – The measure in which a service or piece of information is protected from unauthorized disclosure;
- **Integrity** – The measure in which a service or piece of information is protected from illegitimate and/or undetected modification;
- **Authenticity** – The measure in which a service or piece of information is genuine, and thus protected from personification or forgery;

The first step on protecting the Smart Grid communication is trying to prevent the access of malicious attackers to the communication infrastructure. This can be addressed with physical security whose main objective is to safeguard equipment and information from unauthorized physical access. Therefore, if the communication media is not exposed to attackers, they won't be able to eavesdrop and tamper with information.

When physical security is not enough to prevent the access of attackers there are other security mechanisms that should be applied to protect the Smart Grid from intrusions.

4.3.7.1 Confidentiality

Information confidentiality is primarily accomplished with cryptography. Cryptography is a science that consists of rewriting valuable and comprehensive information in secret code, providing secrecy. In cryptography there are two types of transformations. In the first transformation, called encryption, the original message is transformed into a secret, which is the ciphertext, and in the second transformation, the ciphertext is decrypted into the original message, the plaintext.

Cryptography uses complex mathematical algorithms to perform these transformations with the application of a cryptographic key. This is a relevant characteristic for the mechanism since it enables it to ensure confidentially of the original plaintext by only allowing a correct decryption of the ciphertext by a subject which possesses the same key (symmetric cryptography), or a correspondent key pair (asymmetric cryptography).

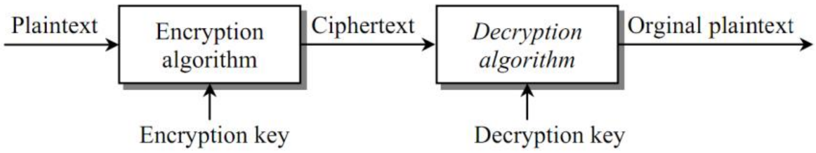


Figure 4—24: Encryption and Decryption process

Obviously, the security of the cryptosystem depends on the secrecy of the keys, which should only be known by the authorized subjects or systems involved in the information flow. Theoretically, without the access to the cryptographic key it is impossible to decrypt a ciphertext into plaintext, even if the details of the cryptographic algorithm are known.

To provide the property of confidentiality, and considering that the crypto algorithm is robust enough to be invulnerable to brute force or statistical attacks, both symmetric and asymmetric cryptography can be adopted to ensure the security of communications.

4.3.7.2 Integrity

Cryptography was introduced as a mechanism to ensure that malicious eavesdroppers would not be capable of interpreting messages flowing in the network. Even if they identify and access the information package, since it is ciphered it has no value to anyone who does not have the key to proceed to decryption.

Here, the objective is to provide integrity to the data in transit, and cryptography is not enough to guarantee it. If malicious users get their hands to encrypted data they are able to modify it in a way that it can transmit false information to the receivers, which will be incapable of detecting tampering and if any change was made over the original message.

Data integrity can be accomplished with hash functions. They are well-defined procedures which use mathematical functions to convert a message into a fixed-size message digest, called hash code or hash-sum. The best way to look at the hash code is as a unique fingerprint of an original message processed both by the sender and receiver.

The sender will deliver to the receiver the encrypted ciphertext as well as the hash of the original plaintext. First, the receiver decrypts the ciphertext received and then, by computing the hash function of the resulting plaintext will be able to compare the hash code he received from the sender and the one resulting from his own hash computation. Whenever these match, data integrity is ensured.

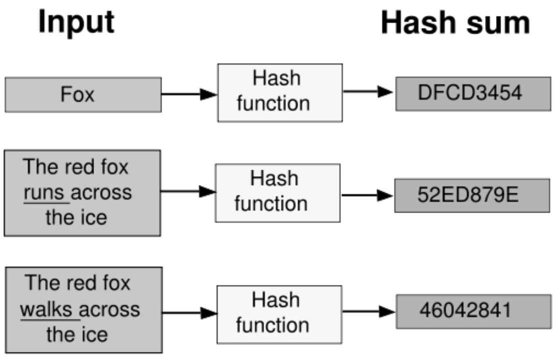


Figure 4—25: Hash Function operation

4.3.7.3 Authentication

Previously we described mechanisms that should be applied to ensure the confidentiality and integrity of the communication. Applying both mechanisms will ensure that a malicious user will not be able to eavesdrop and modify messages in transit. The one security property that also needs to be addressed is authenticity. It is important to guarantee such a property since if a malicious user is able to inject messages in the communication media, the receiver will not be able to acknowledge if it came from an authorized user or not. In a secure communication it is imperative for the receiver to be confident about the sender of the message. This property is provided by asymmetric cryptography or public-key cryptography. The mechanism requires two different keys, the private and public keys. The first is used to lock and encrypt the plaintext and the second to unlock and decrypt the ciphertext. The public key is known by the public and the private key remains private to its owner. There are two different procedures for the mechanism:

- If the lock or encryption key is the one published then the system enables private communication from the public to the unlocking key's owner;
- If the unlock or decryption key is the one published then the system serves as a signature verifier of documents locked by the owner of the private key.

We are interested in the second procedure since it allows a sender to demonstrate the authenticity of a message. The sender applies a mathematical scheme by signing/encrypting the message with its own private key producing the digital signature. Once the receiver gets the signed message he will only be able to decrypt the message using the sender's public key, which key pairs with the sender's private key, which will then prove the authenticity of the message.

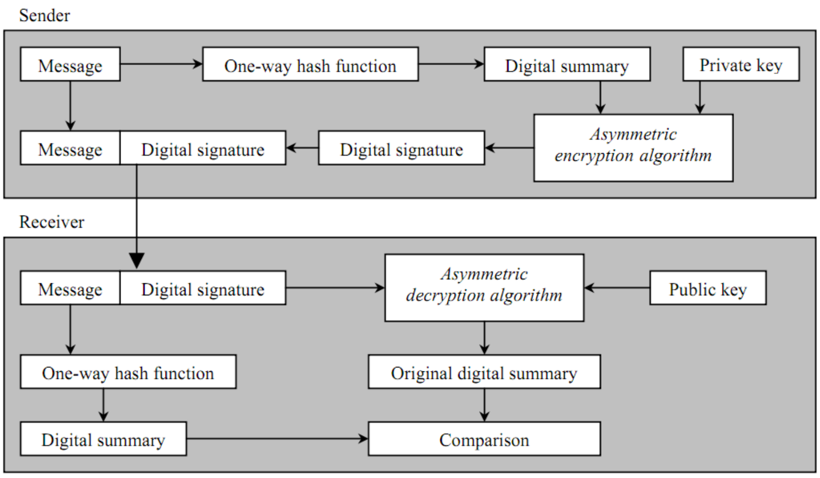


Figure 4—26: The process of creating and verifying digital signature

The adoption of these mechanisms is imperative to protect the Smart Grid communications from malicious abuse. Access to the communication media and to an unprotected protocol can lead to information exposure, information degradation and modification, and a clear understanding of the IT infrastructure which can all facilitate the planning for intrusions and malicious acts against the grid and the utilities.

Regardless of the communication technology adopted by the Smart Grid, while defining the functional and technical requirements, security should be one of the main foundations while building the solution. Security must be considered across the project where there should be always a balance between the existing risks for the Smart Grid and the utility and the weight and investment to adopt the security mechanisms to be protected from those vulnerabilities.

One thing is certain: security must be taken seriously and taken into account at all times.

4.3.7.4 Cyber Security Roadmap

Adopting a strategy based on the premise that security will be more effective when planned and designed at earlier phases, a security roadmap should be implemented with focus on the new critical infrastructure. This work should, not only evaluate the technological vulnerabilities and threats on the grid but also the reliability and resilience on a complete different scenario, with an increased number of sensors, decentralized processing and holistic enterprise data management.

The Smart Grid Security roadmap should also be based on a risk analysis in order to identify the quantity of threats to which each vulnerability is exposed and prioritize mitigation procedures.

The Risk analysis is based on the probability to exploit one vulnerability and its effects (exploitation impact).

		Impact				
		Insignificant	Minor	Moderate	Major	Catastrophic
Probability	Almost Certain	Moderate	High Risk	Extreme	Extreme	Extreme
	Likely	Moderate	High Risk	High Risk	Extreme	Extreme
	Possible	Low Risk	Moderate	High Risk	Extreme	Extreme
	Unlikely	Low Risk	Low Risk	Moderate	High Risk	Extreme
	Rare	Low Risk	Low Risk	Moderate	Moderate	High Risk

Figure 4—27: Quantitative Risk Measurement

The table above represents a quantitative risk measurement by considering the impact to exploit one vulnerability and the probability of that happening. The risk grows in parallel with probability and impact and, the worst scenario is high impact with also high probability.

4.4 New grid infrastructures & planning principles (primary equipment/hardware, storage devices)

4.4.1 Impacts of energy policy on grid planning

A common view and objective is that the electricity distribution grid provides a flexible marketplace for electricity usage and distributed generation. The marketplace has to function in a reliable and economically sustainable manner, and it may not create barriers to the targets set by society, such as demand response, connection of small-scale distributed generation to the grid, functions of the electricity trade and various energy-saving measures.

The operation of DSOs is intensively monitored and supervised by economic and technical regulation. The energy policy objectives for the grid development pose various new challenges; for instance, measures aiming at energy saving may rapidly reduce the amount of energy transmitted on the grids, yet having no significant effects on the peak powers that are decisive in the grid planning and dimensioning. The distribution grids have to be developed as economically and efficiently as possible, yet simultaneously ensuring that the grids adapt smoothly to the changes in the electricity market. The long techno-economic lifetime of the grid components, in particular, poses challenges to the grid planning and development; the grids designed today will be in use, at least to a certain degree, for the next 40–50 years.

The question of what the role of a DSO is in the electricity market and in the load control taking place at the customer gateway has a significant influence on the loads seen on the grid. It is likely that a DSO cannot perform the control actions related to demand response and load control. If the DSO controls the loads of electricity end-users, this will have an impact on the balance of an electricity retailer and further, induce costs to a retailer operating in a competitive market, and thereby also indirect costs to the electricity end-user. Thus, a DSO has to adapt to an operating environment where the loads vary dynamically as a result of actions of other parties. This poses considerable challenges to the grid development. A solution to manage dynamic changes is to develop the grid tariffs for instance into capacity-based ones. Tariffs of this kind, being one of the control parameters, have an impact on the implementation of the load control, irrespective of whether the control is performed by a retailer or an end-user.

In addition to the technical and economic aspects discussed in more detail in Sections 4.4.2 and 4.4.3, the objectives and limitations set by the economic regulation and other codes and instructions have to be taken into account in the development of electricity distribution grids (grid planning). The methodology of economic regulation varies significantly between countries. In some countries, the regulation encourages to grid investments, while in some countries, investments are controlled and even strictly limited. The indices associated with the reliability of supply; SAIDI, SAIFI, MAIFI and interruption costs, also varies among countries. The Energy Efficiency Directive steers the development of the DSOs' energy efficiency, in practice, the grid losses. The effects of many new aspects of the Smart Grid concepts, such as distributed generation, energy storages, demand response and the smart customer gateway remain unclear.

The increasing dependency of society on uninterrupted use of electricity has led to tightening limitations on the acceptable duration of long supply interruptions. For instance in Sweden, by law, a single interruption may last 24 hours at maximum. Accordingly, in Finland, new legislation is being drafted where the maximum duration of an interruption is limited to six hours in urban areas and either 24 or 36 hours in rural areas. Along with the traditional grid technology, technologies and functions related to the Smart Grid concept play a key role when striving for the target limits described above.

4.4.2 Loads in 2030

Determination of the electro-technical capacity required of an electricity distribution grid is based on long-term load forecasts and the resulting **peak powers of the grid components** in different grid operating conditions and situations. Traditionally, the energy and power transmitted on the grid have constantly been increasing, and the load models describing the temporal variation (power variation) have been static.

The functionalities and objectives related to the Smart Grid concept significantly change the volumes and temporal distribution of electrical energy and power (load curves) transmitted on the electricity distribution grid. Figure 4—28 illustrates the customer gateway of an individual electricity end-user and the electricity grid. Part of the customer loads are controllable; for instance in the Scandinavian countries, electric heating loads have been controlled since the 1970s with the target of limiting the peak powers of the DSO. In southern countries, again, air conditioning is a viable target for limiting the peak powers.

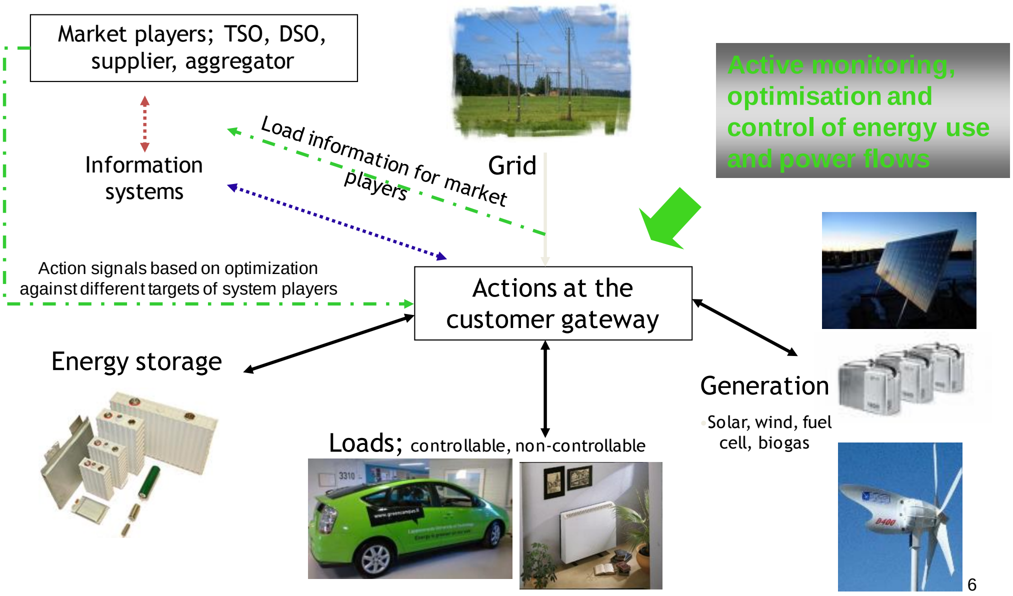
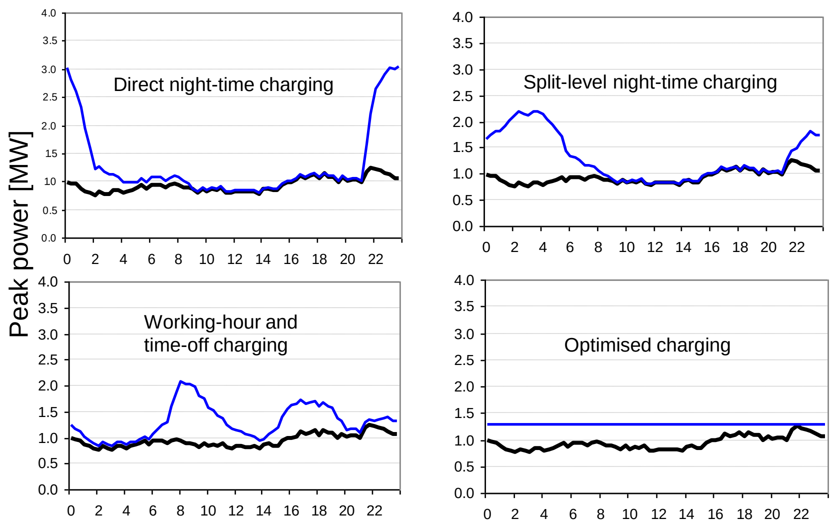


Figure 4—28: Customer grid connection (gateway) in the Smart Grid concept

A **new load type** at the customer gateway are electric vehicles, which do not consume significant amounts of electric energy, yet the vehicle charging powers may be considerable. Further, an electric vehicle is a mobile load. The charging power required by a single car may have an effect on the grid dimensioning in a number of locations: at home, workplace, visiting places, or at a holiday home. Without any control of vehicle charging, the grid impacts may be significant. By the smart control, these impacts can be essentially reduced. Figure 4—29 depicts the effects of alternative charging concepts on the development of the peak power of a target feeder on a medium-voltage grid. In the worst scenario, the electric vehicle charging may almost triple the grid peak power, while in a theoretical optimum case the amount of energy required by vehicles can be delivered without an increase in the peak power.



Rural area feeder:
- Peak load of the day: 1.25 MW
- Minimum load of the day: 0.75 MW

- **Number of electric cars: 750**
- Driving distance: 57 km/car,day
- Energy consumption: 0.2 kWh/km
- Charging energy: 11.5 kWh/car,day
  → 8.6 MWh/day for all cars

- Charging power: 3.6 kW/car
- **Additional power: 0 – 1.75 MW** (depending on charging method)

Charging energy is equal in each charging alternative

Figure 4—29: Impact of alternative EV charging principles on the peak power of a medium-voltage feeder

A new functionality in the customer gateway is the rapidly increasing **end-user electricity generation**. The amount of solar panels in particular has grown and will rapidly increase also in the future. The powers of solar panels vary from a few kilowatts (single-family house) to hundreds of kilowatts (industrial building roof) and even up to megawatts (farm field). The peak operating times of solar panels are approx. 800–1200 h/a depending on the geographical and regional location. Contrary to expectations, the energy yield of solar panels can be significant also in the Nordic conditions; for instance in Finland the annual solar radiation is nearly equivalent to the value in northern Germany.

The development of small-scale wind power has been slow, and also the future prospects are moderate because of the low energy production capacity of small-scale wind power (peak operating times being only a few per cent) and technical challenges (parts requiring maintenance, erection of towers).

Along with the development of **energy storages** and **battery technology** in particular, also the economical storage of electricity is moving from theory into practice. In the first stage, the energy is stored in one direction only in the batteries of electric vehicles, and it is not possible to transfer energy from the batteries back to the grid. There are no technical obstacles to supplying electrical energy from batteries back to the grid, but the obstacles come from the costs of the technology. Using a unit of energy (kWh); (charging, discharging) in a battery reduces the battery lifetime, and from the perspective of the grid load control, the induced cost is too high. The issue is addressed in more detail in section 4.4.4.

The customer gateway between the grid and the end-user is not only an electro-technical interface. The customer gateway is developing into an on-line telecommunications connection between the electricity end-user and different parties in the electricity market. In the initial stage, the connections are based on AMR meters, which have already been installed in many countries (e.g. Italy, Finland) at almost all electricity end-users. In addition to energy and power metering data, various other data are transferred through the gateway for instance on supply interruptions, voltage quality and disturbances on the low-voltage grid (e.g. neutral wire break). In addition, load control functionalities can be implemented through the gateway. The load control can be based for example on steering the electricity consumption to low-cost hours, electricity retailer balance management and using loads in the power balance management of the electricity system under normal and disturbance conditions (reserve capacity).

The above conditions pose multiple new challenges to the prediction of the peak powers and energy volumes of different grid components in the long term. For instance the questions related to the number of electric vehicles in 2030, the competitive strength of batteries in 2030 and the volume of distributed generation on the grid in 2030 are not easily answered, and the results include plenty of uncertainty. However, the grids built today will still be in use in 2050. Hence, grid planning should produce development plans that can be modified in process of time as more exact load data are obtained.

Figure 4—30 illustrates the general effects of changes in the Smart Grid environment on the volumes of power and energy transmitted on the electricity distribution grid when compared with the present situation (origin in the figure). Most of the actions reduce the peak operating time of the grid loads. For instance an electricity end-user's own energy generation (action k in the figure) decreases the amount of energy transmitted on the grid, but does not usually reduce the peak powers of the grid. It is even possible that the grid peak powers increase when the power supplied by solar panels to the grid at low-consumption times exceeds the peak powers of the loads. It is also worth pointing out that compared with the use of electricity, local generation is temporally less evenly distributed because of random variation; for instance, when the weather is sunny at noon in a certain area, all solar panels produce the maximum power. Practical experiences of situations like this have been reported for example in Germany.

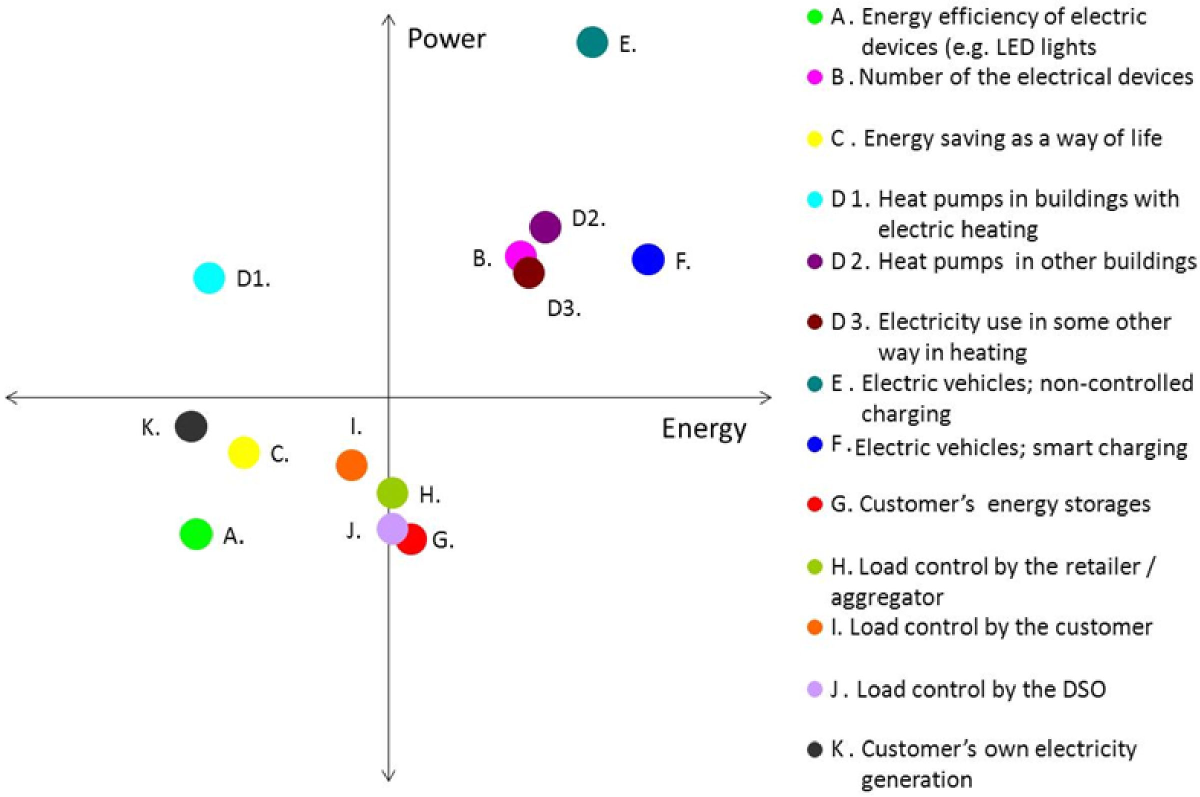


Figure 4—30: Effects of different actions on the power and energy transmitted on the distribution network

4.4.3 Objectives and challenges in the planning of the electricity distribution grid

Planning of electricity distribution grids includes several tasks. The time span of grid design can be even several decades for instance in a situation where area reservations for a new 110kV line are made 20–30 years before the actual construction. The tasks related to the grid design and planning can be divided into the following categories:

- strategic planning
- long-term development planning
- target planning (grid design)
- field planning
- structural planning
- work planning

In all planning phases, the target is to find such a technically feasible solution, the long-term total costs of which can be minimised. In general, a planning assignment can be characterised as a minimisation task of the present value of the investment, and loss, outage and maintenance costs occurring during the planning period (Eq. 4.1). The representation below characterises the practical calculation methodology, in which the costs are expressed as a sum of the present values of the annual costs in the planning period:

$$\min \int_0^T \left(K_{\text{inv}}(t) + K_{\text{loss}}(t) + K_{\text{out}}(t) + K_{\text{main}}(t) \right) \mathrm{d}t \approx \min \sum_{t=1}^{T} \left[K_{\text{inv}}(t) + K_{\text{loss}}(t) + K_{\text{out}}(t) + K_{\text{main}}(t) \right] \quad (4.1)$$

where

- $K_{inv}(t)$: investment costs at time t (year t)
- $K_{loss}(t)$: loss costs at time t (year t)
- $K_{out}(t)$: outage costs at time t (year t)
- $K_{main}(t)$: maintenance costs at time t (year t)
- T : duration of the planning period

Minimisation of costs has to be made within the boundary conditions of the planning assignment. Typical boundary conditions are:

- voltage drop may not exceed the allowed limit
- the temperature withstand capability of the conductors may not be exceeded
- the conductors shall withstand fault currents
- the regulations concerning the performance of the protection have to be met; e.g. the functioning of earth fault protection
- electrical safety regulations have to be met; e.g. requirements for earthing voltages

As a result of grid planning, answers are obtained to the questions of **where, why, how and when** investments are to be made in the electricity distribution grid.

The fundamentals of grid planning (development) can be divided into four main categories: electro-technical capacity, grid reliability, mechanical condition and ageing of the grid components.

Considering the **electro-technical capacity requirements**, the key issue and challenge is the prediction of loads (energy, power, temporal behaviour) in the situation described in Section 4.4.2, which includes a very large number of variables for instance in terms of energy efficiency, distributed generation and demand response. The amount of required electro-technical capacity is chiefly determined by the peak power of the grid components. Peak powers can be actively affected by load control, which can be based either on direct load control or price control. When considering direct load control, the key question is who controls the loads (DSO, retailer, end-user, and aggregator). If the electricity retailer is in charge of load control, this may have negative impacts from the perspective of the grid. The situation is similar for an electricity retailer, if the DSO executes the load control.

The grid **reliability requirements**, again, are determined by the demands of society, electricity end-users and producers, and the development of distributed generation and electricity storage technologies. The tendency is towards weatherproof distribution grids also in rural areas. The significance of electricity as part of other infrastructure in society has increased, and the adverse effects of long supply interruptions can no longer be accepted. The objective of a weatherproof grid is to guarantee uninterrupted use of electricity also during and after extremely severe weather conditions (storms, ice loads, floods). In the future, along with the traditional grid technology, local electricity generation, energy storages and switching off non-critical loads will play a key role in securing uninterrupted use of electricity.

The **mechanical condition** of the grid together with **ageing grid components** may be the key contributor to massive grid renovation tasks in many grids. This is a major challenge but also an opportunity. If the electricity grids have to be renovated anyway, this provides an economically efficient opportunity to renovate the grids to meet the new targets. In that case, for example the application of power electronics, DC technology and energy storage may open new flexible opportunities to meet the future demands.

The mutual effects of grid development and planning processes are illustrated in Figure 4—31. With the many challenges related to the grid development, the role of strategic planning is emphasised. As a result of strategic planning, new views are found on various development scenarios concerning the best applicable grid technologies, topologies, parameters applied to calculations in grid planning and operation models. In various development scenarios, for instance the volume of distributed generation, the number of electric vehicles, the scope of changes in heating methods (heat pumps etc.) and the contents of regulation methodology can be varied. As a result of strategic planning, we thus obtain alternative grid development plans applicable to the development scenarios of the Smart Grid concept. The key in the process is flexibility, in other words, capability to adapt swiftly to new, changing development prospects.

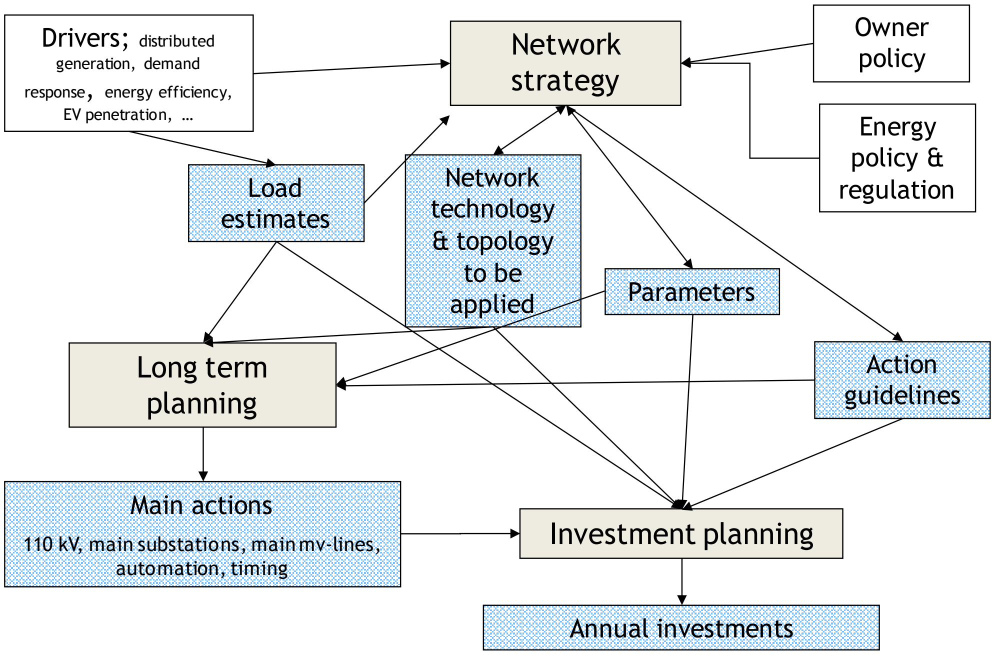


Figure 4—31: Planning process in the grid development

4.4.4 Technologies available

The techno-economic lifetimes of the technologies applied in the electricity distribution grids are typically long, 30–50 years. The lifetimes of automation and protection equipment are shorter, yet up to 10-20 years. However, radical changes in the basic grid technology are not to be expected. The most promising opportunities and expectations are related to the grid automation applying telecommunications connections, and the large-scale utilisation of power electronics and energy storages also in the electricity distribution grids. In particular, if the technical and price development of battery technology follows the trend of the past few years, there will be a huge techno-economic potential in the battery technology as part of electricity distribution systems.

The price competitiveness of power electronics has developed into a favourable direction. The improved performance and energy efficiency together with competitive prices provide opportunities for instance to the application of the LVDC technology as part of the electricity distribution system. In the future, there will also be customers on the grid (e.g. data centres), which would like to be connected to the grid at the DC level. We may suggest that in the future, the grid connection (AC/AC, DC/AC) of not only small-scale generation but also of all other end-users will include power electronics and energy storages, by which the customer’s voltage quality (AC, DC) can be optimised in all circumstances, all short end-user interruptions can be eliminated, and the costs of the electricity distribution system can be reduced. A schematic of an LVDC system is given in Figure 4—32. The DC technology enables energy-efficient connection of distributed generation to the grid and high voltages on the low-voltage side (1500 VDC, ±750 VDC). Along with the development of power electronic components, the energy efficiency of power electronic equipment will improve, thereby enhancing the energy efficiency of the whole electricity distribution system.

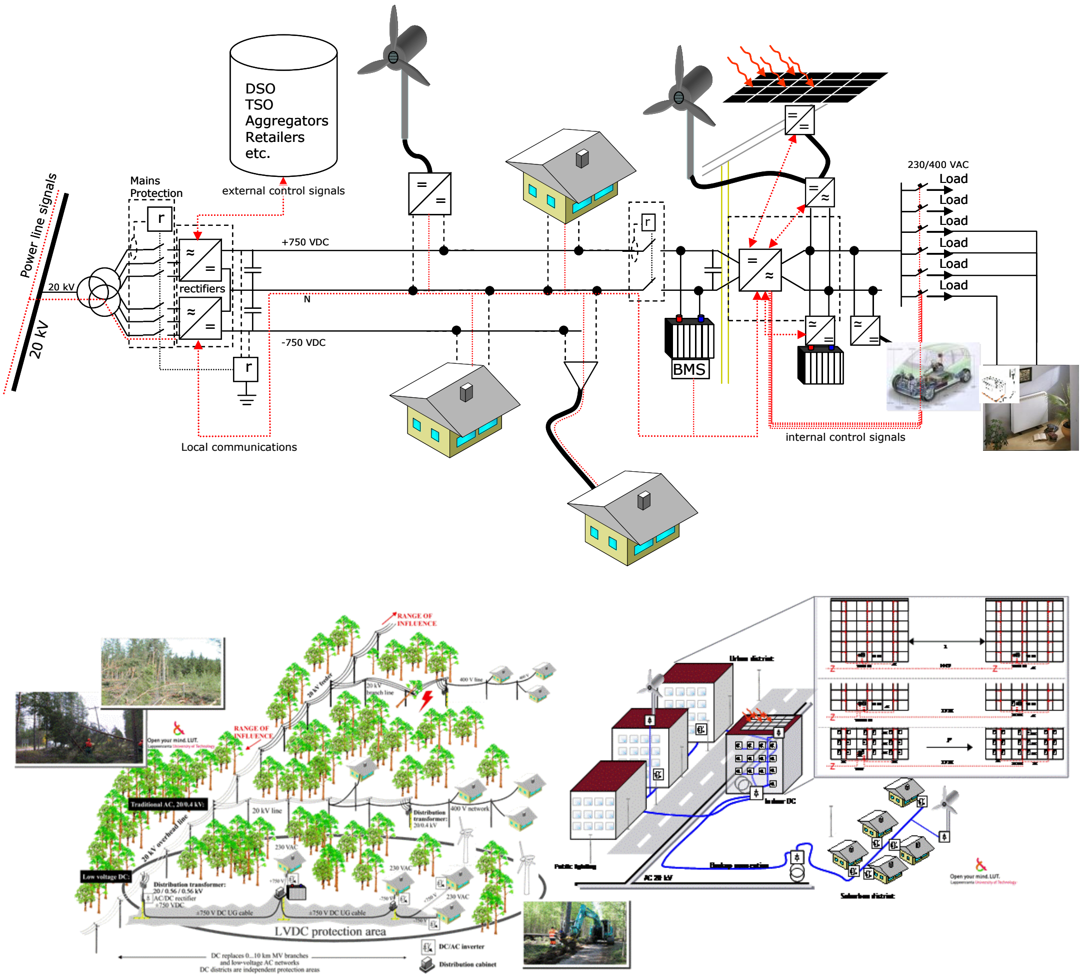


Figure 4—32: Principles of LVDC-based electricity distribution system. Basic equipment structure a) and examples of applications b)

In Finland there are some pilot cases of LVDC systems. In Figure 4—33, the schematic of an LVDC installation in the distribution grid of the case Suur-Savon Sähkö is illustrated. The system voltage is ±750 VDC, and three customers are connected to the DC supply through DC/AC inverters. The charging capacity of the capacitors on the DC side is sufficient to eliminate the customer high-speed automatic reclosing. In the near future, energy storages (batteries) and small-scale generation (solar panels) will be connected to the DC grid.

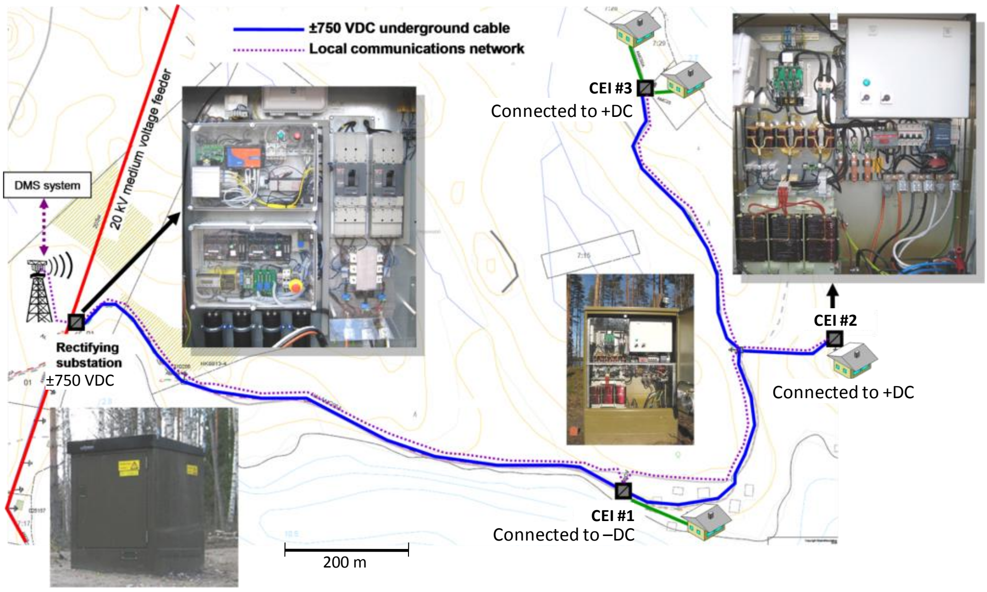


Figure 4—33: Schematic of an LVDC-based electricity distribution system, case Suur-Savon Sähkö, Finland

The price competitiveness of battery technology is assumed to develop favourably also in the future. At present, using batteries as part of an electricity distribution system (cutting of peak power, backup power) is economically feasible only in certain special cases (seldom-occurring peak cutting). The reason for this is the high purchase price of batteries (800–1000€/kW) and their limited lifetime (maximum number of charging cycles - 2000–3000 times). On average, the price for an energy unit used in a battery (charging, discharging) is about 20cent/kWh, Figure 4—34. With the most recent battery solutions, the price is as low as 10 cent/kWh. If/when the price of an energy unit can be brought down to 2–4cent/kWh, which is reached for instance with 15,000 battery charging events and 400–500€/kW investment price or 200€/kWh investment price and 5,000–10 000 battery charging events the application potential of batteries will be significant in the distribution grids in the future.

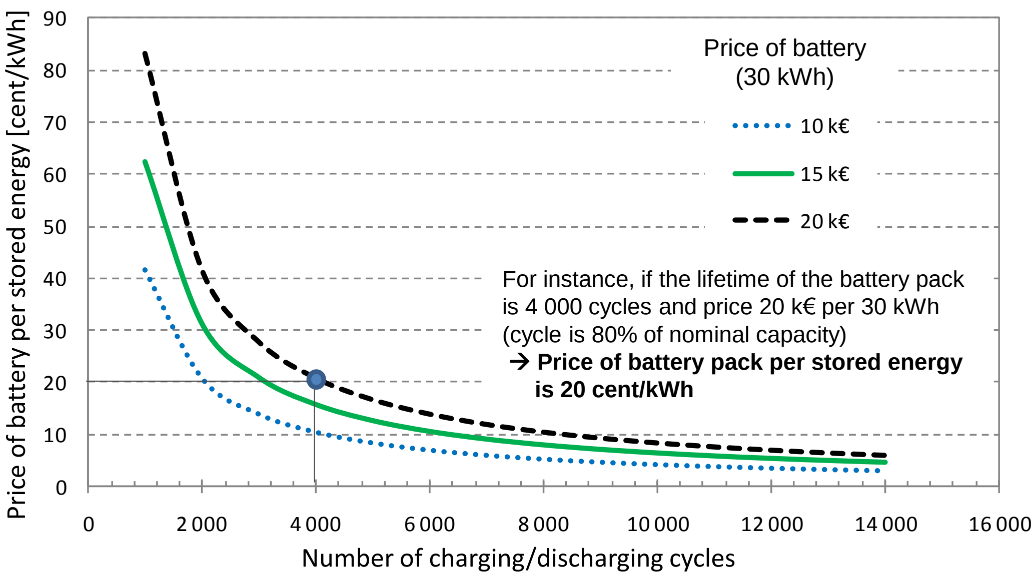


Figure 4—34: Price of battery (30kWh) per charged/discharged energy (snt/kWh) as function of their lifetime (number of charging and recharging cycles)

The advancements in battery technology may provide a solution to the risk management of power forecasts, which involve a high amount of uncertainty. For instance if/when the number of electric vehicles significantly increases, also the price development of batteries has been positive. This, again, provides the DSOs with an opportunity to manage power either in the DSO's own grid or by energy storages on customers' premises.

The following case demonstrates economic effects of battery energy storages in a low-voltage network with residential customers. The customers have residential houses heated by electricity (direct electric heating and electric heating with a water storage, heat recovery). Typical annual and daily load curves are presented in Figure 4—35.

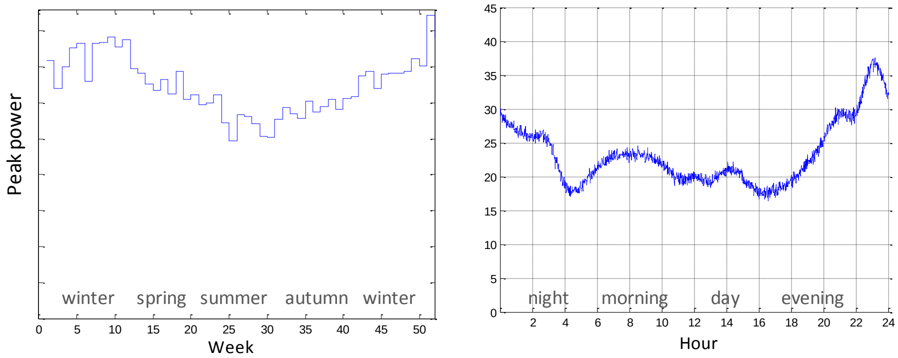


Figure 4—35: Annual (a) and daily (b) load curves of residential customers (electric heating with a water storage)

From the annual load curve we can see that the maximum load of the year is in wintertime. This is a typical situation in the Nordic countries. From the viewpoints of electricity distribution and transformer cooling, winter-time peak loads are easier to handle than summer-time peaks. Figure 4—35b shows that the peaks are scheduled in the evening time. The highest peak occurs at 22-23 hrs, when electric heating is automatically switched on.

The economic effects and the amount of required or delayed investments can be estimated by defining the transmission or distribution- capacity-related average marginal cost of the network (€/kW). The average marginal cost is based on the network replacement value and the maximum load of the year, and it describes how much the network capacity costs for the distribution company per each peak load kilowatt. For instance, if the network replacement value is 1M€ and the distribution capacity of the network is 1MW, the average marginal cost is 1€/W or 1000€/kW.

$$\text{Reinforcement} = \text{Average marginal cost} \cdot \Delta P \tag{4.2}$$

We have to remember that the use of average marginal costs supports network analyses in large-scale analyses; in other words, too target-specific cost analyses should be avoided. In this case, the focus is on the low-voltage network. Based on the replacement value and the present peak power of the network, the average marginal cost is 320€/kW. A change in the network capacity has an effect on the distribution fee (cent/kWh). The additional network investments will eventually be paid by the end-customers. This can be determined when the annuity of reinforcement costs (€/a) is compared with the annual delivered energy in the network.

$$\text{Network value per delivered energy} = \frac{\text{Reinforcement}}{\text{Annual energy}} \tag{4.3}$$

By (Eq. 4.2), we can define an estimate for the saved reinforcement cost. The costs of energy stored in batteries are based on the principle presented in Figure 4—34. Figure 4—36b shows the presented economic limit for the peak reduction in the case network. In the break-even point, the costs of the use of batteries and savings from the avoided or delayed network reinforcements are equal. In this case, the economic break-even point is reached if the charged and discharged energy from batteries for peak cutting is 1.75MWh/a. By charging this energy in the batteries at low-load moments and discharging the energy back to the network at peak moments, about 19kW cut from the present peak power can be reached (Figure 4—36a). If the target for the peak cut is higher than this, the charged and discharged energy needed for the purpose will wear out the batteries (shorten their life-times), causing more costs than the benefit obtained from the network capacity savings.

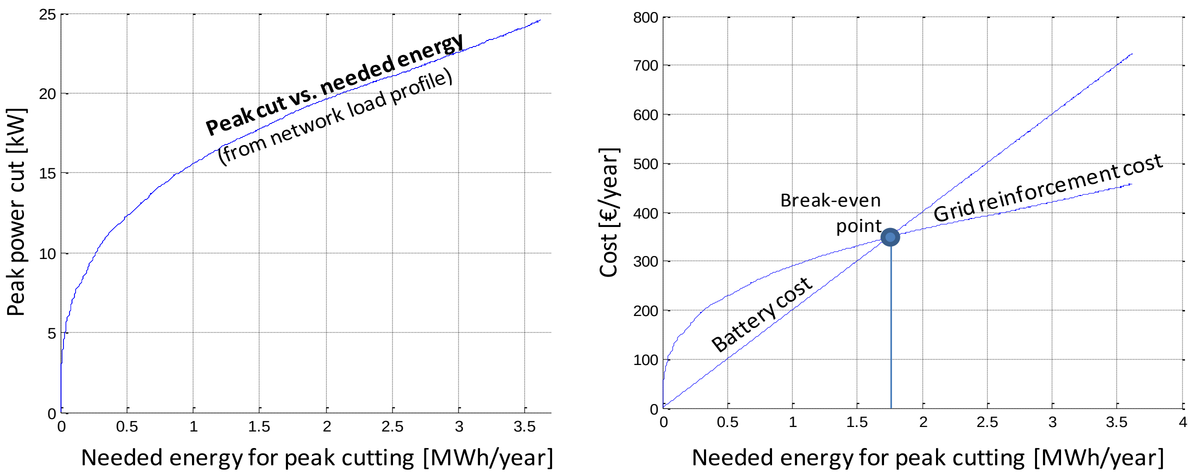


Figure 4—36: a) Peak cut vs. needed energy (taken from the network load profile) b) Economic limit for peak cut

Figure 4—36b shows that a positive difference in the grid reinforcement costs and battery costs is highest with a low use of energy storages (batteries). In Figure 4—37, savings related to the case are presented in more detail. The maximum savings for the case network (136€/a) are reached when the peak cut is 10.9kW. The charged/discharged energy required for the peak cut is 342kWh/a.

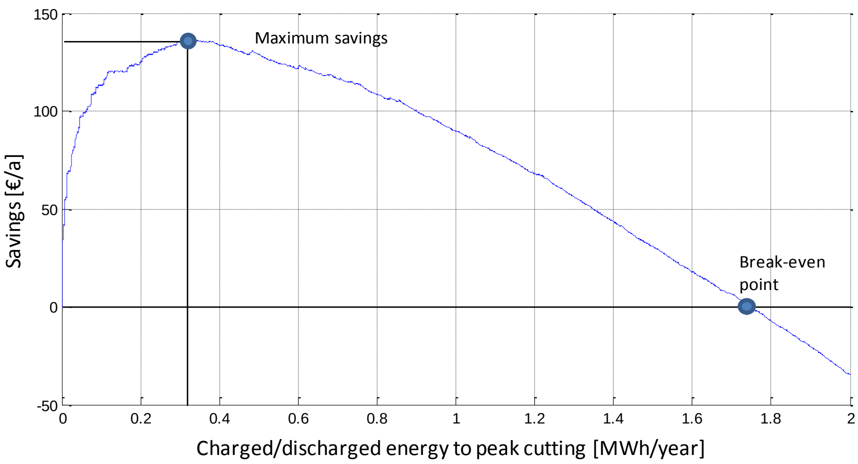


Figure 4—37: Savings vs. needed battery capacity (charging/discharging)

Large-scale application of **grid automation** enables nearly uninterrupted electricity distribution by automatic disconnection, connection of backup supplies and use of distributed generation (self-healing grids, microgrids). Efficient use of automation allows the maximum use of the distribution system capacity also in challenging circumstances. This reduces the grid investment needs and costs. Assessing the development of grid automation is thus among the key actions in the strategic planning of the grids.

Underground cabling is increasingly applied also in rural areas, where the load density is low. The main reason for large-scale underground cabling is the objective to eliminate long supply interruptions during and after extreme weather conditions. Large-scale underground cabling poses challenges to the grid planning; the key issues are the selection of grid topologies suitable for the Smart Grid environment, future transmission capacities, earth fault management in neutral-isolated medium-voltage grids and introduction of cost-efficient installation methods (ploughing instead of excavation).

4.4.5 Reliability of supply and voltage quality

The **reliability criteria** set for the electricity distribution grids are constantly tightened up. In many countries, the reliability indices SAIFI, SAIDI, MAIFI and outage costs are included in the regulation of electricity distribution grids, and they have a significant impact on the allowed return of the DSOs. The durations of long interruptions during major storms are limited also by legislation by defining an upper limit for the allowed interruption duration, for instance 24 hours.

The Smart Grid operating environment brings new challenges to the reliability criteria set for the grids. Increasing amounts of distributed generation are being connected to the grid, and this generation has to be transmitted reliably to the market. On the other hand, the numbers of customers' own generation and possibly energy storage devices are increasing, which will allow at least a limited use of electricity during grid disturbances. To some extent, the requirement level will thus increase, but on the other hand, requirements will be less stringent as microgrid-type of solutions will become more common. In general, we may state that the acceptability of long supply interruptions (hours) will decrease while short interruptions will be allowed as the customers' own technological solutions will be able to eliminate such interruptions.

Considering **voltage quality**, the challenges are twofold: the number of load sources on the grid is increasing, and the harmonics caused by these loads cause voltage distortion on the distribution grid. Therefore, the grid impedance should be as low as possible. On the other hand, the voltage quality can be improved by power electronics. If/when power electronics becomes more common in the connection points of electricity end-users, the voltage quality can be improved to meet the quality criteria at the customer gateway, and if required, larger voltage fluctuations and harmonics levels can be allowed on the grid. In particular, if there are short term load peaks on the grid, it may be economically beneficial to adjust the voltage level by applying power electronics at the customer connection point without a threat of degrading the energy efficiency of the entire distribution system (including increases in losses).

4.5 Data Warehousing

4.5.1 Context

As earlier chapters of this paper have explained, in the Smart Grid of the future, requirements for data, and for data to be converted to information, will be several orders of magnitude higher in terms of volume, granularity, and required speed of availability than today. The demand for data and information arises essentially due to the far more integrated nature of the grid, including centralised and decentralised energy resources and consumers (and prosumers). Additional demand for electricity due to decarbonisation policies will also require DSOs to monitor and manage networks far more actively in order to avoid network constraints or conflicts and/or in order to avoid excessive and disruptive investment in traditional network capacity. The diagram below (Figure 4—38) illustrates the more extensive and integrated nature of the future Smart Grid.

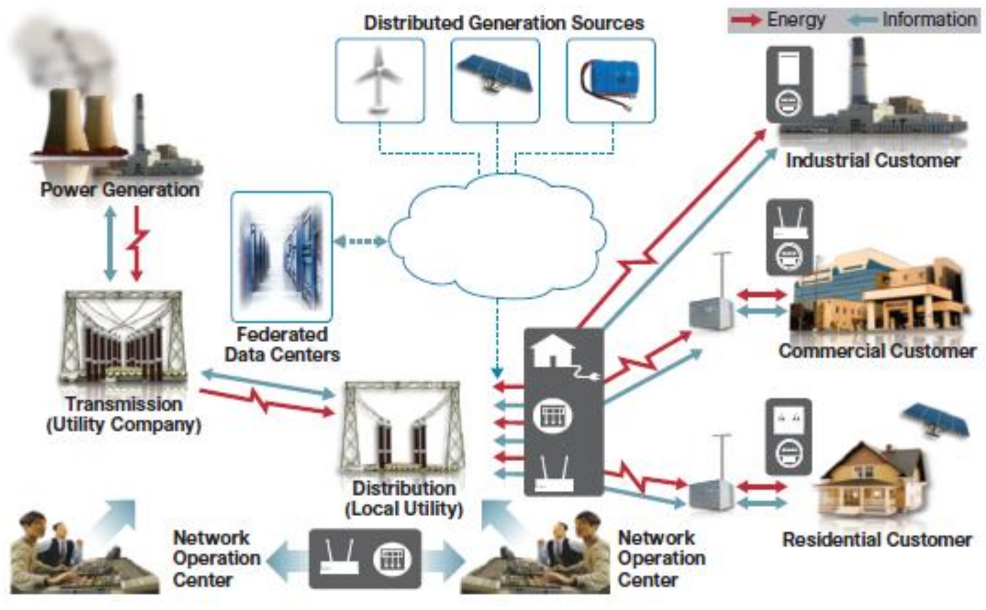


Figure 4—38: Integration of future Smart Grids

4.5.2 The role of Data Warehousing

Data warehouses will play an essential role in sharing and segmenting appropriate information in order to provide a common, standardized and continuously updated data repository. This repository will concurrently serve several enterprise systems and ensure continuous synchronisation such that all systems have (or can readily access) the latest information regarding the operational state, duty or condition of a network asset. Centralised management control and visibility of Smart Grid information is essential but bringing together the disparate pieces of information in different formats for a cohesive and functional view will be a challenge; especially where legacy (largely non-integrated) systems have to be renewed and integrated into the new centralised management system. One immediate benefit is reduced operational costs and improved customer service through better field force management.

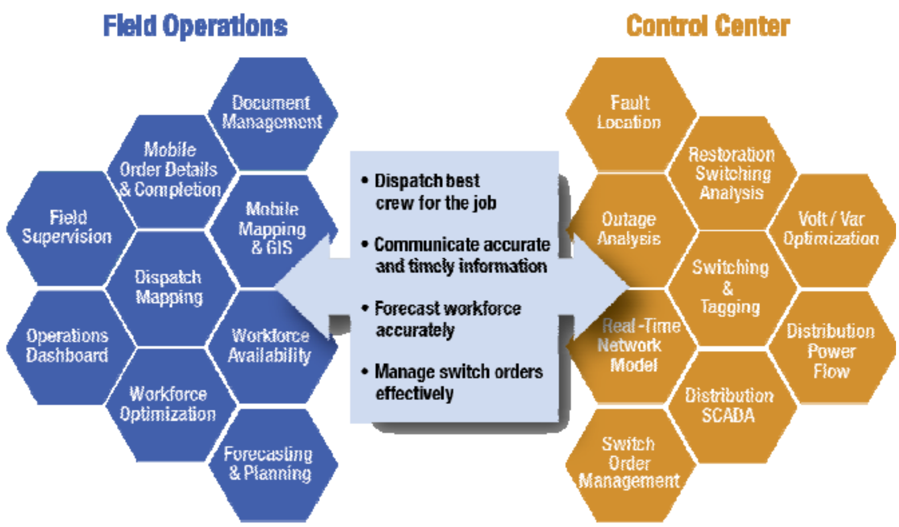


Figure 4—39: Source: Ventyx

Even in this simple subset of a DSO's operation, the need for integration of disparate sources of data is very apparent. Benefits include:

- Dispatching the most suitable field team (with regard to skills, location, materials, equipment)
- Communicating accurate and timely information
- Better work planning ensuring the right field resources are available where and when they are needed
- Better planning, executing and documenting of switching operations (including during unplanned / outage events)

However, the need for data integration extends beyond that necessary to optimise field force resources and includes: asset condition data, network and component loading data, and circuit outage data. Additional data sources include automated smart metering data, and reference data held in Network Management, SCADA, Asset Management, Work Management, GIS, and Customer Information Management Systems. The diagram below (Figure 4—40) illustrates typical Smart Grid data management architecture.

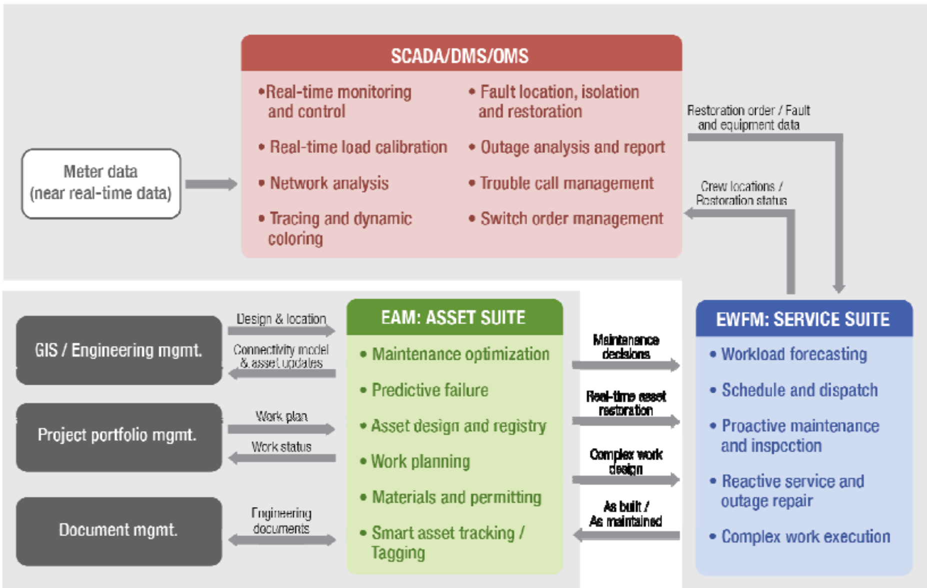


Figure 4—40: Typical Smart Grid data management architecture (Source: Ventyx)

4.5.3 Benefits of Data Warehousing

A well designed integrated system will provide the underlying computing platforms and infrastructure to enable sophisticated data collection techniques and storage for power grid data analysis and optimisation. The numerous benefits include:

Data Management Benefits

- Reduced cost of excess capacity and storage
- Improved resilience and security of the grid
- Essential cyber-security
- Security of private data (e.g. consumer metered consumption)
- Elimination of costs of resolving data conflicts

Grid Management Benefits (from better data management)

- Avoided costs of suboptimal asset and network management decisions due to flawed or incomplete data
- Improved monitoring and diagnostic capabilities
- Extended asset lives
- Enhanced asset utilisation
- Improved load factor

- Reduced losses
- Accurately identifying grid capacity headroom (with regard to thermal, voltage, fault-level and power quality constraints)
- Better optimisation and control of the grid (in terms both of design and normal running and in real time)
- Reduced cost of electricity distribution through better control of demand (including peak shifting/reshaping)
- Ability to integrate DERs (e.g. DG, storage and demand side response) into the management of the grid
- Optimised informed risk-based investment decisions

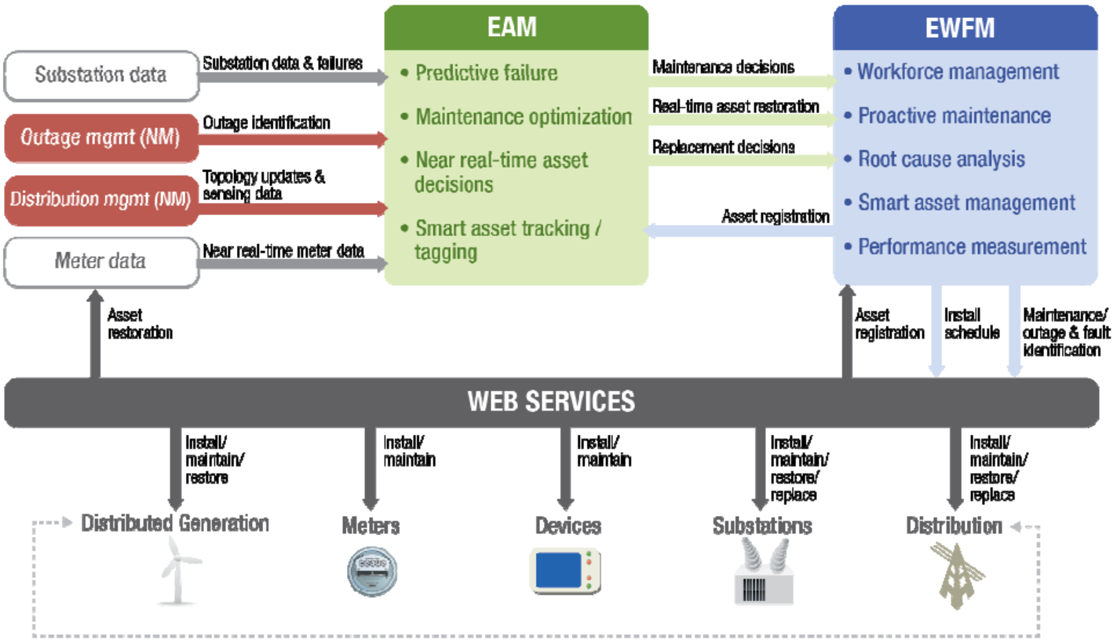


Figure 4—41: Source: Ventyx

In summary, an essential role of data and hence efficient data warehousing is the ability to support all aspects of Smart Grid management including: asset management, network management and field force management.

Asset Management

- Predicting potential functional failure (the 'pf' interval)
- Optimised timing and prioritisation of maintenance and outages
- Predictive asset modelling capability based on real-time data
- Tagging and tracking of smart assets to gain better predictive and analysis capabilities of smart asset performance
- Greater performance and reliability of smart assets
- More detailed and precise asset lifecycle location and condition data

Network Management

- Pinpointing and diagnosing Smart Grid issues and initiating timely and effective responses
- Real-time network state management
- Real-time asset connectivity and connection status
- Automated failure notification to repair crews
- Remote access monitoring and reporting of smart assets

Field Force Management

- Increase field productivity through timely and accurate information
- Enhanced proactive preventive maintenance capability from holistic integrated asset information
- More comprehensive root-cause analysis
- Smarter customer related services (including appointments and self-servicer portals – e.g. for appointment booking)

4.5.4 Data Warehouse Structure

The actual design and organisation of a data warehouses may take many forms but the concept of a centralised common information repository is common. That said, decentralised and virtual systems are now gaining popularity and are seen by some to be the future, especially given the potential explosion of data accompanying Smart Grids in the longer term. However, for a Smart Grid, as well as the central data warehouse, an Operational Data Store (ODS) will be a key component. A typical high level structure is illustrated below, showing the relationship between the ODS and the Data Warehouse, and between the Data Warehouse and analytical applications.

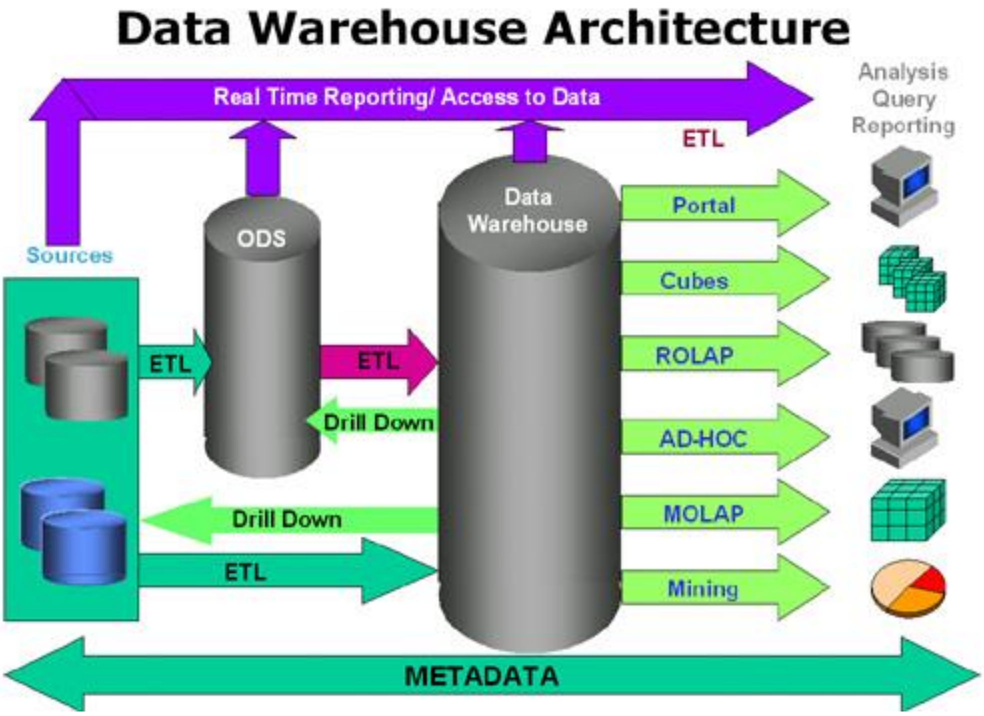


Figure 4—42: Data Warehouse Architecture

Data from individual source operational systems go through Extraction, Transformation and Loading (ETL) processes and are retained in an ODS before being loaded into the Enterprise Data Warehouse. The logic of this approach is based on two fundamental principles:

- Operational and tactical decisions such as operations scheduling, maintenance and outage management are critically different to strategic decisions such as asset replacement, reinforcement and maintenance planning. Hence a tailored data mart scheme provides optimised decision support for target users
- Increasingly with Smart Grids, real-time decisions and automation sequences using peer-to-peer communications will be made remotely from the centralised systems (including the central Network Management System), for example through a decentralised network management system. This is because the necessary two-way communications systems from remote terminal units (RTUs) might be expensive to establish and/or suffer from communications latency which might undermine the integrity and

reliability of automation sequences. The data warehouse may therefore contain a snapshot; local data staging areas will conduct the ETL stage with the data from local operational systems

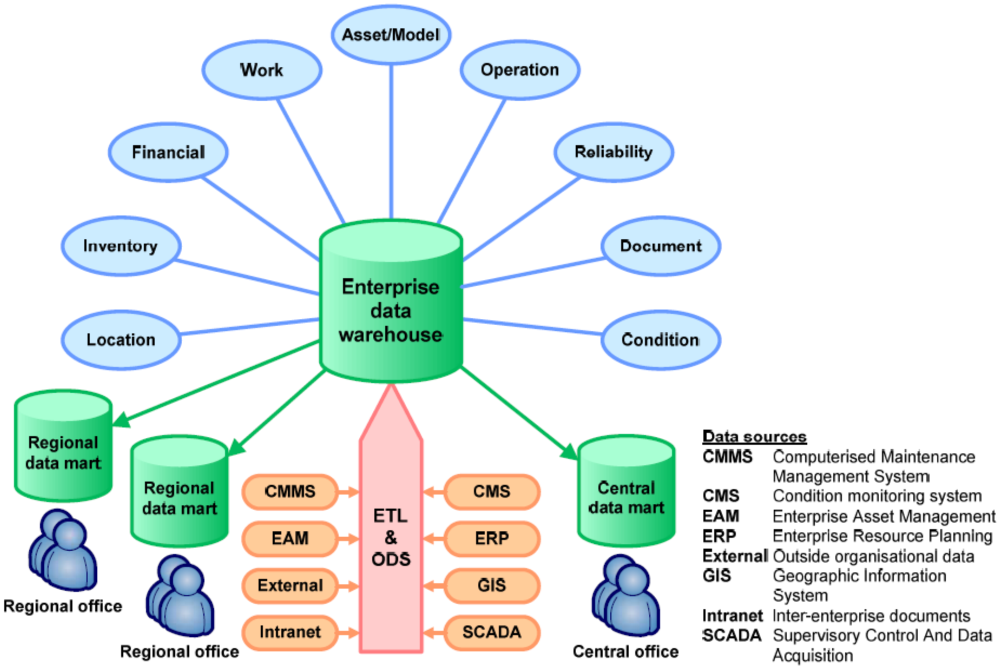


Figure 4—43: Data Warehouse Links

4.5.5 Conclusion

From the above it is clear that the future Smart Grid will have a huge dependency on comprehensive and highly integrated information. Hence currency and accuracy of the data from which such information is derived is essential. There can be no future for disparate, non-integrated, and non-synchronised sources of information which are all too typical of traditional utility IT systems.

Consumer, regulator, shareholder and wider stakeholder expectations of the electricity grid will demand the highest standards of Smart Grid management across all performance vectors (reliability, safety, efficiency, integrity, flexibility, quality, etc.).

While much of the debate around Smart Grids tends to focus on the grid network itself, it is a simple fact that however smart the grid assets may be, true Smart Grid performance will be impossible without the necessary foundation provided by not only very high volumes of highly accurate and synchronised data, but the ability of systems to select, mine and integrate that data and undertake the necessary diagnosis to present the required information on which Smart Grid management decisions (often automated) will be made.

The future for Smart Grids appears to lie with strong data warehousing but coupled increasingly with widely decentralised autonomous network management systems which will communicate through the ODS following completion of the necessary automated switching operations such that the ODS and hence Data Warehouse is updated in near real-time but does not participate (i.e. does not interchange data) during the actual switching sequence.

5 International/European Standards/State of the Art in Standardization

Standardization in the context of Smart Grid is predominantly characterized by focusing on interface specifications enabling the interoperability of systems, devices and equipment. This includes:

- Standardized processes and semantics for power system data exchange
- Communication standards for the syntactic and semantic understanding between the ICT systems and devices in order to achieve an interoperable ICT infrastructure
- Interconnection standards for integration and use of primary and secondary system equipment

The next section gives an overview on standardization organizations that develop and maintain Smart Grid related standards and on related international activities to coordinate the Smart Grid standardization. Further the Smart Grid standardization process is presented which comprises a systematic approach for standard development based on use cases and the Smart Grid architectural model. After this an overview on standards for data models, communication protocols and for grid interconnection is given in respect to current applicability and future development.

5.1 Standardization Organizations and International Activities

The International Electrotechnical Commission (IEC) is the world's main standardization organization for electro-technologies. Besides the International Organization for Standardization (ISO) and the International Telecommunication Union (ITU), IEC prepares and publishes international standards for all electrical, electronic and related technologies.

On international level there are several roadmaps and initiatives dealing with Smart Grid standardization. IEC SG3 (Strategic Group) has developed a roadmap including a list of relevant standards with definitions and descriptions and recommendations for further developments [61]. On regional level European CEN-CENEL-ETSI Report on Standards for Smart Girds [62], NIST Interoperability roadmap [63], German DKE Smart Grid Standardization roadmap [64], Japan's roadmap to international standardization for Smart Grid [65] and Strong and Smart Grid China roadmap [66] are further examples. Common to all these roadmaps is the reference to the standards and activities of IEC TC 8 "System aspects for electrical supply" [67], IEC TC 13 "Electrical energy measurement, tariff- and load control" [68] and IEC TC 57 "Power systems management and associated information exchange" [69] as relevant for Smart Grids.

Technical Committee IEC TC 8 prepares and coordinates in cooperation with other committees standards with emphasis on overall system aspects of electrical supply systems. This includes terminology, electric system reliability, connection practices, characteristics of energy supply and a Smart Grid use case repository as common basis for committees working on Smart Grid related topics.

Technical Committee IEC TC 13 prepares standards in the field for metering equipment and systems, including smart metering systems, for electrical energy measurement, tariff- and load control, customer information and payment, for use in power stations, along the network, and at energy end users, as well as to prepare international standards for meter test equipment and methods.

Technical committee IEC TC 57 prepares standards for power system management and related information exchange. This includes communication interface, information security and data model specifications covering power utility automation (protection, substation automation, distribution automation), DER management, SCADA, EMS, DMS, market communication as well as information exchange between power system and home, building and industry automation. IEC TC 57 has published 127 standard documents. Currently 39 projects are in development by 12 working groups.

In Europe, in 2010 the European Commission has issued the mandate M/490 "Standardization Mandate to European Standardization Organizations (ESOs) to support European Smart Grids deployment" to the European standardization organizations CEN/CENELEC and ETSI. The mandate's objectives comprise the development of a Smart Grid reference architecture, the development of systematic and sustainable standardization processes with emphasis on use case management, and the provision of a first set of standards as a basis for Smart Grid implementation in Europe [70]. In addition the Working Group for Smart Grid Information Security will answer the technical and organizational needs for sustainable "state of the art" Smart Grid Information Security and acts as an enabler for proper data protection and data security for all participating actors [71].

5.2 Smart Grid Standardization Process

The international standardization organizations have recognized that Smart Grid standardization requires a coordinated and systematic effort for standards development which is able to cope with the characteristics of the Smart Grid – its crosscutting nature (various stakeholders from different domains), its complexity (interconnection of different systems and devices), its heterogeneous maturity (installed base, application of new technologies, new use cases) and its evolutionary character(need to migrate from legacy systems).

Throughout the European Smart Grid mandate M/490 a process is currently being setup which is intended to orchestrate the international Smart Grid standardization activities. The process bases on an use case driven approach to coordinate the work across technical committees from different standardization organizations (Figure 5—1).

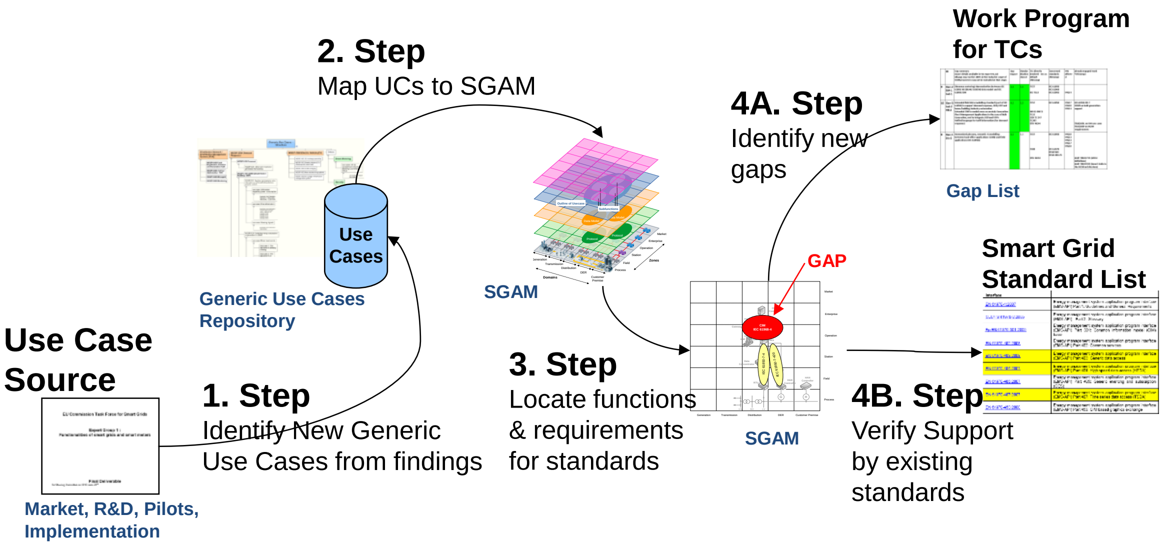


Figure 5—1: M/490 Smart Grid standardization process

Input for this process are use cases and requirements gathered from the market, research and pilot projects and field implementations. These use cases are analysed in respect of generic contents and managed through a use case repository [72]. In the next step the use case is mapped to the Smart Grid Architectural Model (SGAM) in order to determine if the use case is supported by already existing standards or if there is a gap indicating the need for a standard. In case of a missing specification, the need is documented in a gap list and handed over to the responsible committee which is in charge of preparing the standard. In case of support by an existing standard, this standard can be listed as appropriate for Smart Grids [73].

This process combines new methodologies which are increasingly applied in standardization – use case driven requirements engineering, system architecture engineering and UML modelling techniques.

Use cases were identified as a common means to describe the required Smart Grid functionalities (see chapter 3) as they are easily accessible to most of the involved stakeholders coming from one of the various domains. They provide ways to collect and formalize (to a certain extent) requirements on complex systems, from user request down to solution specification. With an associated sequence diagram, a use case can express timely interactions among functions and services, thus providing requirements for interface specifications.

System architecture is required to reveal interactions, relationships and dependencies of the elements of a complex system. For this purpose the Smart Grid Architecture Model (SGAM) is used to describe the functional connections and the information and communications technology relationships between Smart Grid domains and participating systems and subsystems [74]. Aspects of interoperability have been taken into account as well as issues of availability, information security, and energy efficiency.

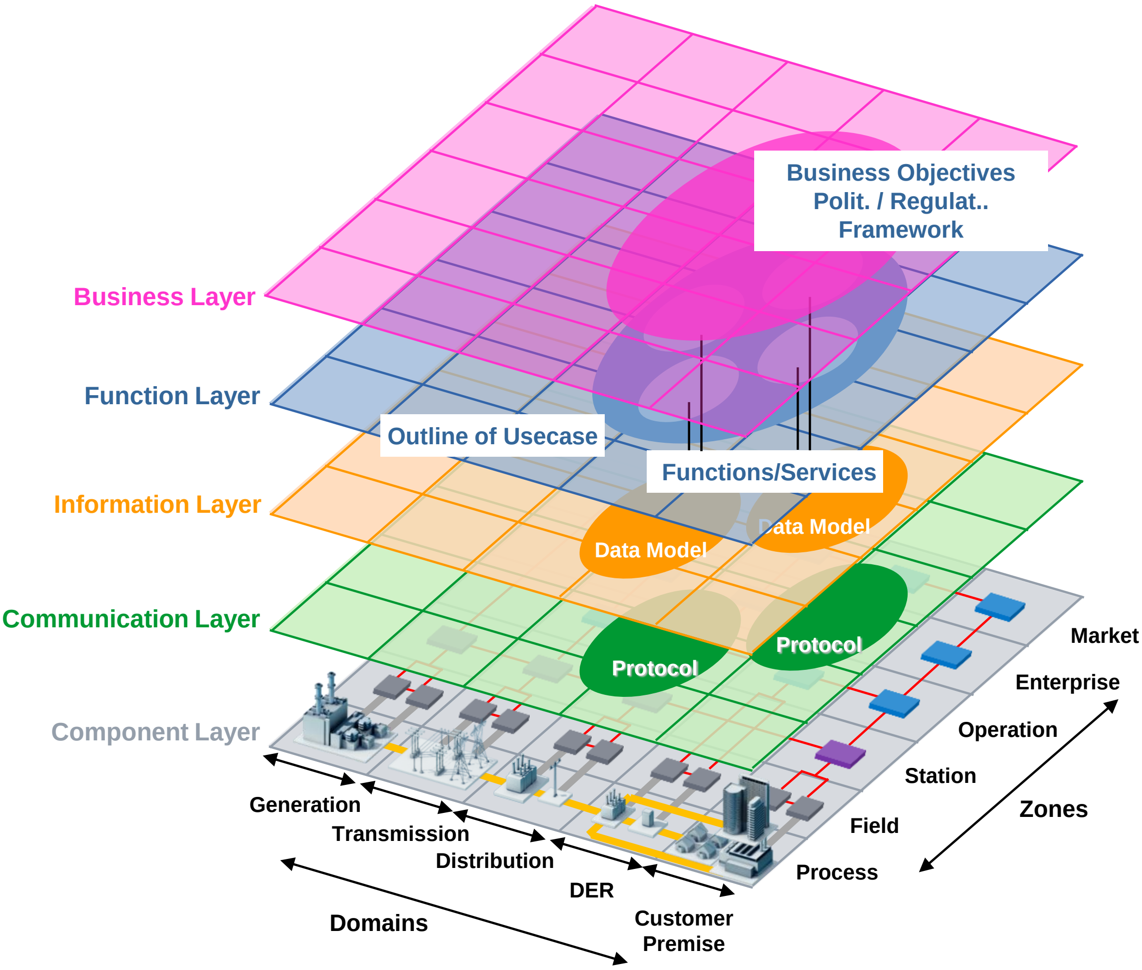


Figure 5—2: Smart Grid Architecture Model (SGAM)

The foundation of the SGAM architecture model is the Smart Grid plane that spans the domains of the power generation and conversion chain as well as the hierarchical zones of power system management. Interoperability is depicted by the five superimposed model layers “Component”, “Communication”, “Information”, “Function”, and “Business”. This means that all the layers have to be covered by specifications in order to achieve interoperability for a given use case. Using this model, it is possible to display and compare different approaches to Smart Grid solutions so that differences and commonalities between various paradigms, roadmaps, and points of view can be detected. The use cases including functions and services, sequence diagrams, functional and non-functional requirements are then mapped to the Smart Grid Architectural Model (SGAM). Being able to represent technical and domain aspects, it is possible to locate the responsibility of committees of standardization organizations in the diagram.

UML modelling techniques – a well-developed methodology in software engineering – is used in standardization for the formal description of use cases. Furthermore development and management of semantic data model standards is increasingly done with support by UML tools, e.g. IEC TC57 with standards IEC 61968 / IEC 61970 (CIM) and IEC 61850. The industry is striving towards model driven engineering, expressing the needs for efficient use of standards. UML methodologies enable technical committees to prepare electronic data model standards in order to fulfil industry needs.

5.3 Data Model Standards

In the context of communications, data models provide the semantic understanding for simplifying information exchange between cooperating systems and applications. The standards used in power system management have evolved from signal oriented data model standards (defining basic data types, e.g. single point status) to object oriented data model standards able to represent application specific semantics (defining data classes, e.g. attributes of a circuit breaker). Data model standards can be represented in the Information Layer of Smart Grid Architecture Model.

The concept of decoupling data models from communication protocols and technologies is increasingly applied in power system related standardization. By introducing an adaptation layer between data model and communication services (e.g. Abstract Communication Service Interface (ACSI) in IEC 61850), this allows the flexible use of different communication technologies. This technology independence guarantees long-term stability for the data model and opens up the possibility to cope and benefit with the evolution of communication technologies.

The data model standards which have been identified applicable for Smart Grid ([61] - [66]) can be grouped into four semantic domains including revenue metering and demand response (Figure 5—3).

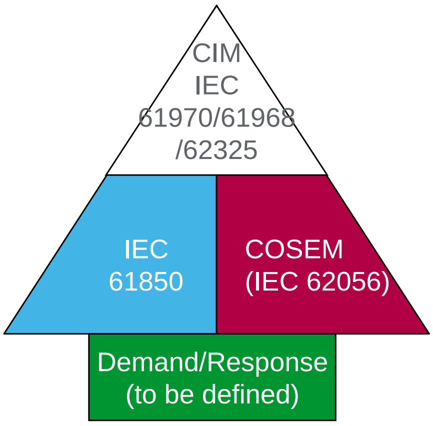


Figure 5—3: IEC main semantic domains (power supply side)

The data model standards applicable for Smart Grid can be grouped into four semantic domains including revenue metering and demand response (Figure 5—2):

- The Common Information Model (CIM) semantic domain, covered by the series of standards IEC 61970, IEC 61968 and IEC 62325 (the last one is specific to the energy market transaction modelling);
- The IEC 61850 semantic domain, which covers the whole supply side at field level as well as in a near future, the connection with the electric vehicle charging station and the interface with smart users;
- The Companion Specification for Energy Metering (COSEM - IEC 62056) data exchange model, dedicated to revenue metering;
- And finally, a demand-response data exchange model, currently in development by IEC TC57 WG21, focusing on interfaces to smart users of the Smart Grid.

Use cases in Smart Grid increasingly feature data exchange between different semantic domains. In order to support this by standards dedicated joint working groups have been setup in IEC which develop specifications for the interoperation between IEC 61850, CIM and COSEM data models.

5.4 Communication Protocols

Communication protocols specify the syntactic format and rules for information exchange within and between systems. In the context of Smart Grid communication protocols define how information – based on data models standards – is exchanged between Smart Grid systems, devices and components. In Smart Grid applications specific non-functional requirements need to be considered, such as cyber security, reliability, quality of service, coexistence.

In the following table (Table 5-1) the communication protocols are listed which have been identified as relevant ([61] - [66]) in respect to the systems applying. The status of the standard indicates, if it is already published as International Standard (IS), Technical Specification (TS), Technical Report (TR) or is in preparation. Besides these global accepted standards, regional specifications are in use e.g. DNP3 and MODBUS protocol.

The work on IEC 61850 is currently focusing on heavily deployed scenarios typically observed outside the substation down to the customer/producer interface and in DER management use cases. For this Web services technologies are currently investigated to be standardized.

Table 5-1: Communication Protocols

Systems	Sub Systems	Standard	Status
Transmission Management System	EMS SCADA System	IEC 61970-4xx, “Energy management system application program interface (EMS-API)”	Published (IS)
		IEC 62325, “Framework for energy market communications”	Published (IS)
		IEC 60870-6, “Telecontrol equipment and systems - Part 6: Telecontrol protocols compatible with ISO standards and ITU-T recommendations “	Published (TS)
	Substation Automation	IEC 61850-8-1, “Communication networks and systems for power utility automation - Part 8-1: Specific communication service mapping (SCSM) - Mappings to MMS (ISO 9506-1 and ISO 9506-2) and to ISO/IEC 8802-3	Published (IS)
		IEC 61850-9-2, “Communication networks and systems for power utility automation - Part 9-2: Specific communication service mapping (SCSM) - Sampled values over ISO/IEC 8802-3	Published (IS)
		IEC 61850-90-1, “Communication networks and systems for power utility automation - Part 90-1: Use of IEC 61850 for the communication between substations”	Published (TR)
		IEC 61850-90-2, “Communication networks and systems for power utility automation - Part 90-1: Use of IEC 61850 for the communication between substations and control center”	In preparation
		IEC 60870-5-101, -103, -104, “Telecontrol equipment and systems. Part 5: Transmission protocols”	Published (IS)
	WAMS	IEC 61850-90-5, “Communication networks and systems for power utility automation - Part 90-5: Use of IEC 61850 to transmit synchrophasor information according to IEEE C37.118”	Published (TR)
		IEEE P37.118, “IEEE Standard for Synchrophasors for Power Systems”	Published
	Condition Monitoring	IEC/TR 61850-90-3, “Communication networks and systems for power utility automation - Part 90-3: Use of IEC 61850 for condition monitoring”	In preparation
	FACTS	IEC 61850-90-4, “Communication networks and systems for power utility automation - Part 90-7: IEC 61850 object models for FACTS”	In preparation
Distribution Manageme nt System	DMS SCADA System	IEC 61968, “Application integration at electric utilities - System interfaces for distribution management”	Published (IS)
		IEC 60870-6, “Telecontrol equipment and systems - Part 6: Telecontrol protocols compatible with ISO standards and ITU-T	Published (IS)

Systems	Sub Systems	Standard	Status
		recommendations "	
	Substation Automation	IEC 61850-8-1, "Communication networks and systems for power utility automation - Part 8-1: Specific communication service mapping (SCSM) - Mappings to MMS (ISO 9506-1 and ISO 9506-2) and to ISO/IEC 8802-3	Published (IS)
	Feeder Automation	IEC 60870-5-101, -103, -104, "Telecontrol equipment and systems. Part 5: Transmission protocols"	Published (IS)
		IEC 61850-90-6, "Communication networks and systems for power utility automation - Part 90-6: Use of IEC 61850 for distribution automation")	In preparation
	Power Quality	IEC 61850-8-1, "Communication networks and systems for power utility automation - Part 8-1: Specific communication service mapping (SCSM) - Mappings to MMS (ISO 9506-1 and ISO 9506-2) and to ISO/IEC 8802-3	Published (IS)
	MV/LV substation	IEC 61850-8-1, "Communication networks and systems for power utility automation - Part 8-1: Specific communication service mapping (SCSM) - Mappings to MMS (ISO 9506-1 and ISO 9506-2) and to ISO/IEC 8802-3	Published (IS)
	Smart Reclosers	IEC 61850-8-2, "Communication networks and systems for power utility automation - Part 8-2: Specific communication service mapping (SCSM) - Mappings to web-services	In preparation
DER management system	Hydroelectric power plants	IEC 61850-7-410, "Communication networks and systems for power utility automation - Part 7-410: Hydroelectric power plants - Communication for monitoring and control"	Published (IS)
	Wind power plants	IEC 61400-25-4, "Wind turbines - Part 25-4: Communications for monitoring and control of wind power plants - Mapping to communication profile"	Published (IS)
	Photovoltaic, Storarge, VPP, Microgrid	IEC 61850-7-420, "Communication networks and systems for power utility automation - Part 7-420: Basic communication structure - Distributed energy resources logical nodes IEC 61850-90-7 "Communication networks and systems for power utility automation - Part 90-7: IEC 61850 object models for photovoltaic, storage, and other DER inverters"	Published (IS) In preparation
	Charging station	IEC 61850-90-8 "Communication networks and systems for power utility automation - Part 90-8: IEC 61850 Object models for electrical transportation"	Published (TR)
Smart Metering		IEC 62059, "Electricity metering - Data exchange for meter reading, tariff and load control" IEC 61334, "Distribution automation using distribution line carrier systems"	Published (IS) Published (IS)
Cross-cutting	Security	IEC 62351, "Power systems management and associated information exchange - Data and communications security"	Published (TS)

5.5 Network interconnection requirements

In the field level the network interconnection creates value added for all stakeholders through synergies: electricity prices can be flexibly adapted to supply and demand in due consideration of environmental aspects and markets can better react to such price fluctuations.

The interconnection requirements for distributed generation equipment can be extremely complicated in some states or utilities and no consensus standards have been emerged at this time to guide the integration of renewable and other small electricity generation and storage sources into the electric network.

At the national level, the Institute of Electrical and Electronics Engineers (IEEE) has developed a series of standards that address interconnection. The base standard – IEEE 1547, "Standard for Distributed Resources Interconnected with Electric Power Systems" – provides requirements relating to the performance, operation, testing, safety considerations, and maintenance of the grid interconnection. Additional standards in the series address interconnection system testing, applications, monitoring, information exchange and control, intentional islanding, and network systems. See the IEEE 1547 Series website for more information

European standards in accordance with EN 50160, EN 50438, EN 50439 provides requirements for micro-generator interconnection. The European Commission mandates ENTSO-E (European Network of Transmission System Operators for Electricity) to draft network codes for 2012 and beyond. It includes requirements for Grid Connection applicable to all Generators.

A series of activities are currently happening in EU in order to develop harmonized interconnection requirement and Standards for Distributed energy source; this is the case of CENELEC, through the technical committee TC8X (CLC/TC8X).

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