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PRIORITISATION OF TECHNICAL SOLUTIONS AVAILABLE FOR THE INTEGRATION OF PV INTO THE DISTRIBUTION GRID

D3.1

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1 EXECUTIVE SUMMARY

PV GRID PROJECT

In 2012 a consortium of 21 partners from 16 EU countries started the PV GRID project with the objective to prepare the grounds for the large-scale integration of photovoltaic (PV) systems in distribution grids across Europe and bring forward concrete suggestions on how this can be achieved.

In order to integrate higher shares of PV and other distributed energy resources (DER) in saturated distribution grids, voltage and congestion limitations need to be overcome by technical measures.

In a first phase of the PV GRID project, the most appropriate technical solutions have been identified. The suitability of the technical solutions has then been analyzed by involving the expertise of distribution grid operators (DSOs) and other experts. Based on these results, the PV GRID consortium will investigate in a second phase, normative and regulatory actions that will allow a swifter and more economical implementation of the most promising technical solutions.

AVAILABLE TECHNICAL SOLUTIONS ENHANCING THE GRID HOSTING CAPACITY FOR PV INTEGRATION

With the target of increasing the distribution grid hosting capacity of PV generation but also of other distributed energy resources, the PV GRID consortium addressed two main constraints the distribution grid would have to cope with: the voltage rise and the congestion management.

The subsequent list of technical solutions for enhancing the grid capacity for PV integration has been identified in the literature and within the PV GRID consortium as the most relevant for the current and future electrical distribution networks. The identified technical solutions are categorized in *DSO*, *Prosumer* and *Interactive* solutions. *DSO* solutions are installed and managed on the grid side and do not require any interaction with the consumers or the PV plants. The *Prosumer* solutions are installed before the meter and react based on the grid characteristics at the point of common coupling, without any communication with the DSO. The *Interactive* category requires a communication infrastructure linking the hardware located in different grid locations.

DSO SOLUTIONS

Network reinforcement - Further grid hosting capacity is provided by additional cable and transformer capacity installations.

On Load Tap Changer (MV/LV transformer) - The OLTC device is able to adjust the lower voltage value of an energized transformer.

Advanced voltage control (HV/MV transformer) - This solution includes new control methods for existing HV/MV transformers with already installed OLTC.

Static VAR Control - Utilizing Static VAR Compensators (SVC) enables to provide instantaneously reactive power under various network conditions.

DSO storage - Storing electricity with a central storage situated in a suitable position of the feeder enables to mitigate voltage and congestion problems.

Booster Transformers - Boosters are MV-MV or LV-LV transformers which are used to stabilize the voltage along a long feeder.

Network Reconfiguration - Revising network operational conditions by reconfiguration, in particular at the boundaries between feeders in MV networks, is a solution to ensure the voltage profiles stay within regulated boundaries in distribution networks.

Advanced Closed-Loop Operation - Two feeders are jointly operated in a meshed grid topology controlled by Smart Grid architecture to decrease the circuit impedance.

PROSUMER SOLUTIONS

Prosumer Storage - Storing electricity at prosumer level enables to mitigate voltage and congestion problems provided that a reduction of the feed-in peaks can be ensured.

Self-consumption by tariff incentives - With a fixed tariff structure (e.g. feed-in price lower than consumption price), the prosumer is incentivized to shift its electricity consumption in order to reduce its injected PV energy. A maximum feed-in power based tariff (e.g. kWh price set to zero or to negative values above some feed-in power limits) could further support in reducing injected PV peak power.

Curtailment of power feed-in at PCC - The meter at the customer's site controls that the feed-in power is never above the contracted maximum power or above a fixed value (e.g. 70% of the installed PV capacity as implemented in the German Renewable Energy Act). This solution requires the meter to be able to control down the PV production or to activate a dump load.

Active power control by PV inverter P(U) - Voltage and congestion problems can be solved by curtailing the PV feed-in power. Contrary to the fixed power curtailment as described in previous solution, the LV grid voltage is used as an indicator for the grid situation and for the curtailment level.

Reactive power control by PV inverter Q(U), Q(P) - Providing reactive power as a function of the local voltage value [Q=Q(U)] or as a function of the active power production [Q=Q(P)], limits the voltage rise caused by distributed generation.

INTERACTIVE SOLUTIONS

Demand response by local price signals - Demand response is triggered by local price signals available only to consumers located in feeders which experience voltage and/or congestion problems.

Demand response by market price signals - Demand response is triggered by electricity market price signals, which are identical for consumers wherever they are located.

SCADA + direct load control - In critical grid situations, DSOs or energy aggregators are allowed to remotely activate or curtail dedicated consumer loads, based on agreed contract.

SCADA + PV inverter control (Q and P) - The level of reactive power provision and the active power reduction of dedicated PV inverters are remotely controlled by a feeder supervisory control system.

Wide area voltage control - All controllable equipment (like transformers with OLTC, static VAR compensators, dedicated loads and PV inverters) are coordinated to optimize voltage and power factor in the whole DSO area. Smart grid technologies are applied to measure the voltage and power factor at several points, controlling the equipment, coordinating and optimizing the generation and load.

EVALUATION OF THE MOST RELEVANT TECHNICAL SOLUTIONS ALLOWING THE GRID INTEGRATION OF HIGH SHARES OF PHOTOVOLTAICS

Grid simulations allow a direct comparison of different technical solutions with the drawback of representing assumptions of predefined grid topologies. By contrast, the evaluation method used within PV GRID activities aims for a holistic trans-national outcome for saturated grid situations. However, identified technical solutions might not be applicable to every grid situation.

The applied evaluation method is based on national assessments made by DSOs from Italy, Spain, Germany and Czech Republic and on a subsequent review made by the PV industry associations involved in the consortium.

Technical solutions have been evaluated considering two grid types (LV and MV) against the following five qualitative criteria:

- Investment costs
- Impact on voltage
- Impact on congestion
- Technology readiness
- Applicability within existing regulatory framework

Performance indicators (cost-benefit, regulatory priority) have been calculated from the different criteria. These results have been complemented by multi-stakeholder workshops. The final results are two priority tables respectively for low voltage (LV) and medium voltage (MV) grids.

LOW VOLTAGE EFFECTIVENESS TABLE

The list of most appropriate solutions (high effectiveness solutions) includes two DSO solutions (the classical network reinforcement and the new product OLTC for MV/LV transformer) and four PROSUMER solutions (storage, reactive power provision by PV inverters and the 2 curtailment variants of PV power). No regulatory barriers have been identified for the DSO solutions (green colour in table). On the contrary, regulatory barriers are present in all countries (red colour in table) with respect to the use of PV curtailment solutions. The solutions *Reactive power control by PV inverters* and *Prosumer storage* can already be applied, but regulatory barriers are present in Czech Republic, Spain and Italy.

Effectiveness of solutions	Technical solution	CZ	DE	ES	IT
HIGH EFFECTIVENESS	Curtailment of power feed-in at PCC	🟥	🟥	🟥	🟥
	Network Reinforcement	🟩	🟩	🟩	🟩
	Reactive power control by PV inverter Q(U) Q(P)	🟥	🟩	🟥	🟥
	Active power control by PV inverter P(U)	🟥	🟥	🟥	🟥
	Prosumer storage	🟥	🟩	🟥	🟩
	On Load Tap Changer for MV/LV transformer	🟩	🟩	🟩	🟩
NORMAL EFFECTIVENESS	SCADA + direct load control	🟥	🟥	🟥	🟥
	Network Reconfiguration	🟩	🟩	🟩	🟩
	Self-consumption by tariff incentives	🟩	🟩	🟥	🟥
	Wide area voltage control	🟨	🟨	🟩	🟨
	Static VAr Control	🟩	🟩	🟩	🟩
	Booster Transformer	🟩	🟩	🟩	🟩
	SCADA + PV inverter control (Q and P)	🟨	🟥	🟨	🟨
	DSO storage	🟥	🟥	🟥	🟥
LOW EFFECTIVENESS	Demand response by local price signals	🟥	🟥	🟥	🟥
	Advanced voltage control for HV/MV transformer	🟩	🟩	🟩	🟩
	Demand response by market price signals	🟨	🟨	🟨	🟥
	Advanced Closed-Loop Operation	⬜	🟩	🟨	⬜

Regulatory priority index - Legend
🟥 Adoption of solution requires regulatory development
🟨 Adoption of solution requires regulatory and technology developments
⬜ Technology is not mature
🟩 Can be applied where problems occur

MEDIUM VOLTAGE EFFECTIVENESS TABLE

The list of most appropriate solutions (high effectiveness solutions) includes three DSO solutions (the classical network reinforcement, OLTC for HV/MV transformer and network reconfiguration), three PROSUMER solutions (un-supervised reactive power provision by PV inverters and curtailment variants of PV power) and one INTERACTIVE solution (supervised control of PV active and reactive power). No regulatory barriers have been identified for the DSO solutions (green colour in table). On the contrary, regulatory barriers are present for all other solutions in nearly all countries (red colour in table, with exception of un-supervised reactive power provision in Germany).

Effectiveness of Solutions	Technical solution	CZ	DE	ES	IT
HIGH EFFECTIVENESS	Network Reinforcement	🟩	🟩	🟩	🟩
	Reactive power control by PV inverter Q(U) Q(P)	🟥	🟩	🟥	🟥
	Curtailment of power feed-in at PCC	🟥	🟥	🟥	🟥
	Active power control by PV inverter P(U)	🟥	🟥	🟥	🟥
	Network Reconfiguration	🟩	🟩	🟩	🟩
	SCADA + PV inverter control (Q and P)	🟥	🟥	🟥	🟥
	Advanced voltage control for HV/MV transformer	🟩	🟩	🟩	🟩
NORMAL EFFECTIVENESS	Static VAr Control	🟩	🟩	🟩	🟩
	SCADA + direct load control	🟨	🟨	🟥	🟥
	Self-consumption by tariff incentives	🟩	🟩	🟨	🟥
	Wide area voltage control	🟨	🟨	🟩	🟨
	DSO storage	🟥	🟥	🟥	🟨
	Prosumer storage	🟥	🟩	🟥	🟩
LOW EFFECTIVENESS	On Load Tap Changer for MV/LV transformer	🟩	🟩	🟩	🟩
	Booster Transformer	🟩	🟩	🟩	🟩
	Demand response by local price signals	🟥	🟥	🟥	🟥
	Demand response by market price signals	🟨	🟨	🟨	🟥
	Advanced Closed-Loop Operation	⬜	🟩	🟨	⬜

	Regulatory priority index - Legend
🟥	Adoption of solution requires regulatory development
🟨	Adoption of solution requires regulatory and technology developments
⬜	Technology is not mature
🟩	Can be applied where problems occur

2 INTRODUCTION

FOREWORD

Energy imports currently contribute significantly to the trade deficit of the EU. A vigorous expansion of renewable energies is currently a recognised way to confront the dependency on energy imports. European fossil fuel resources diminish steadily and have an extremely negative CO_2 balance. Therefore, the development of photovoltaic (PV) and other renewable energy sources (RES) is not only environmentally, but also economically a valid alternative.

The PV GRID project aims to indicate how the integration of large amounts of PV and RES in the energy supply system may be facilitated, and aims to point at obstacles that hinder the development of RES. This project focuses on PV technology without neglecting other RES entirely.

The distribution network covers the low voltage, medium voltage and high voltage levels up to 110 kV and is by this definition distinguished from the transmission grid. Due to the project's scope, issues that are associated with the transmission system, like frequency stability, are not discussed here. However, the PV GRID consortium is aware that system issues and the role of distribution networks in system operation will be increasingly important with an expansion of renewable generation. A more detailed overview on the electricity system operation with high share of PV is offered in Section 4 and in references [9], [10], [11].

THE PV GRID PROJECT

PV GRID is a transnational collaborative effort in which sixteen national and European solar industry associations, three distribution system operators, a policy consultancy, a technical consultancy and a regulatory research institute collaborate within the Intelligent Energy Europe Programme. The project is coordinated by the German solar Industry association, BSW-Solar.

The overall goal of the PV GRID project is to address the **regulatory**, **administrative** and **technical requirement barriers** hampering the integration of PV into the electricity distribution grids in Europe through two main actions:

- the **assessment and comparison of national frameworks for PV development** in the 16 participating counties;
- the prioritisation of technical solutions available for **enhancing PV hosting capacity in distribution grids** and the formulation of regulatory and normative recommendations for their adoption.

Assessment of National Frameworks for PV Development

The assessment and comparison of national frameworks for first developing and then operating PV systems in 16 European countries is achieved by means of an **extensive research activity** involving fifteen national industry associations and coordinated by the policy consultancy eclareon GmbH, based in Berlin, Germany. The results of this assessment are mainly disseminated through the online PV GRID database and a series of national forums that will take place in each of the participating countries during the spring and summer of 2013.

Enhancing PV Hosting Capacity in Distribution Grids

The objective of enhancing PV hosting capacity in distribution grids is pursued by an initial **prioritisation of available technical solutions**, analysed by involving distribution grid operators (DSOs) and other electricity sector experts. This task mainly leverages on the experience of three DSOs: ENEL Distribuzione (Italy) RWE Deutschland (Germany) and Lumen (Czech Republic) and is coordinated by DERLab, an association of laboratories and research institutes in the field of distributed energy resources based in Kassel, Germany.

Starting from the most efficient solutions identified and the barriers to their large-scale application, the project consortium will proceed to formulate European wide regulatory and normative recommendations. This second step of the action will be led by the IIT research institute of the Comillas Pontifical University based in Madrid, Spain. The results of this process will be mainly disseminated in the aforementioned national forums and in an additional series of national and European workshops targeted at DSOs, regulators and policy-makers taking place in 2014.

National and European Level Communication

The national and European level communication activities for the dissemination of project results are coordinated by EPIA, the European PV Industry Association based in Brussels, Belgium.

WORK PACKAGE 3

Within PV GRID, Work Package 3 (WP3) is focused on the challenges linked to the integration of high shares of PV electricity into the distribution system. The main goal of this work package is to prepare the grounds for large-scale integration of PV systems in distribution grids across Europe.

The work package has set up 3 working groups in which project partners and external experts collaborate in researching and analysing the issues and discuss solutions on a trans-national level. The main tasks of the working groups are to:

- Review and evaluate the most appropriate technical solutions for integrating PV systems on the distribution grid infrastructure
- Recommend normative and regulatory solutions that allow for swifter and economic implementation of these solutions

The **normative recommendations** will address administrative barriers and other obstacles that either DSOs or PV operators have to face when implementing technical solutions that would instead allow for higher grid hosting capacity, such as long permitting times and inappropriate grid codes.

Regulatory recommendations, on the other hand, will address the framework in which DSO and PV systems owners operate. For instance, a certain national regulatory framework may not allow a DSO to recover the costs of necessary grid-enhancing investments. Also, a PV system operator may not be correctly incentivized (by means of network fees for instance) to make an efficient use of the distribution grid.

The WP3 is divided in the following tasks:

- T3.1 Initial data collection and set-up of WGs
- T3.2 Analysis, discussion and evaluation of technical PV grid integration solutions
- T3.3 Analysis and discussions of regulatory and normative aspects
- T3.4 Preparation of advisory paper

The present document reports the outcomes of the tasks T3.1 and T3.2. Section 3 provides an overview of PV integration status in Europe. Section 4 introduces the technical challenges associated with grid integration of high shares of PV. In section 5, the identified key technical solutions are presented. In section 6, the solutions are evaluated and prioritised with common criteria (cost, technology readiness, impact on grid hosting capacity, applicability within existing regulatory framework).

3 BACKGROUND – GRID INTEGRATION OF HIGH SHARES OF PV

This section is intended to provide basic statistical information about the status quo of high penetration levels of PV power in distribution grids in Europe and more specifically in the PV GRID four focus countries Czech Republic, Germany, Italy and Spain.

For grid integration studies, the most relevant penetration level indicator is the power penetration level, which is defined as the maximal instantaneous ratio "PV generated power" divided by "load consumed power".

However, assessing PV power penetration in distribution grids is not easy as local integration conditions vary widely from place to place and only national (or regional) statistics are available. It is thus important to notice that the average national (or regional) statistics provided do not reflect the huge heterogeneity of local grid situations, which are due to differences in:

- demand (spatial density, daily and seasonal profiles, flexibility)
- PV generation (spatial density, solar resource profile, position along the feeder)
- grid parameters (topology, feeder and transformer impedances, thermal limits, controllability)

Several indicators are available to estimate the PV power penetration level. For example, the ratio "PV capacity" divided by "Minimum mid-day consumed power" would be a valuable indicator. In case statistics for the "Minimum mid-day consumed power" are not available, they could be replaced by the energy coverage (share) over a specific period (day, month, or year). Depending on data availability, the PV penetration levels could be referenced per country, per regions and/or voltage levels.

It is especially of importance for the PV Grid project to estimate the capacity and number of systems connected to the different voltage levels as the cost and the benefit of implementing a grid measure vary a lot from one voltage level to another. The ease to develop the necessary communication infrastructure required for some measures is for example really different when looking at the low or the medium voltage level. All over Europe, MV grids are more and more automated and the communication means become economically and technically attractive. The picture is completely different when looking at the low voltage for which a proper cost benefit analysis still needs to be conducted for an efficient communication infrastructure.

3.1 Europe

3.1.1 Installed PV capacity

As shown in Figure 1, about 70 GWp of PV was installed by end 2012 in the EU27 contributing to 2.5% of the final consumption.

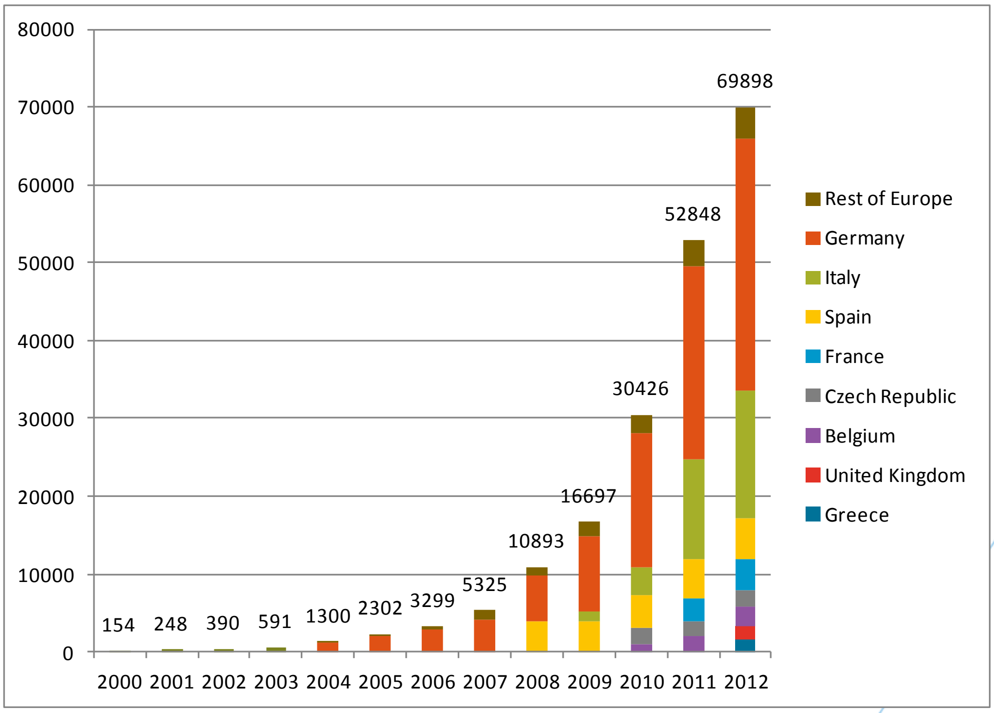

Figure 1 - Evolution of PV capacity in EU 27 (in MWp), EPIA 2013

3.1.2 Spatial distribution of PV

PV capacities are not evenly spread across Europe as can be seen in Figure 2 which represents PV installed capacity per habitant by end of 2011. There are large differences of PV penetration levels between the countries and even larger differences between the regions. In some regions the decentralised PV production currently exceeds the local demand. In particular in these regions, dedicated grid integration measures are already applied by the DSOs.

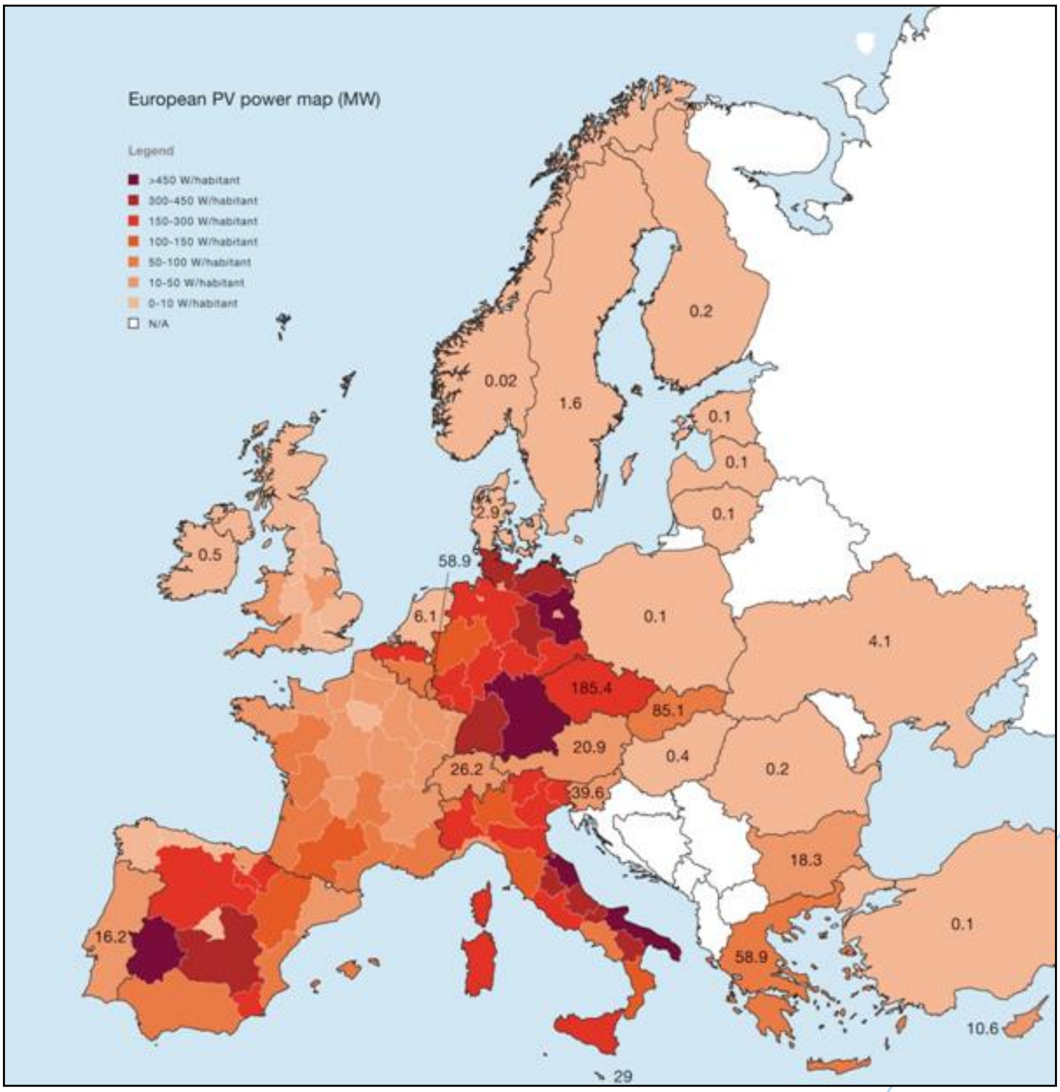

Figure 2 - Spatial spread of the PV installed capacity in EU 27 in Wp per habitant at the end of 2012, (source: EPIA)

3.1.3 Installed PV capacity per voltage level

Figure 3 presents the aggregated number of the PV capacity installed per voltage level. The number for Europe is extrapolated knowing that the collected data covered 92% of the European installed capacity.

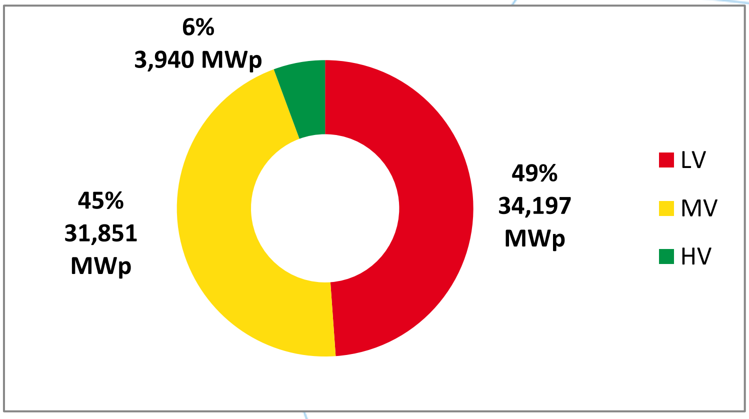

Figure 3 - Estimated capacity per voltage level in Europe at the end of 2012 (source: EPIA, PV national associations in the PV GRID consortium)

From these data, the number of systems per connection level has been estimated in Table 1. This estimation helps to understand the challenge regarding the communication and data exchanges with numerous systems.

Low voltage	Medium voltage	High voltage
≈2,000,000	≈90,000	≈7,200

Table 1 - Estimated number of PV systems per connection level in Europe (source: EPIA)

3.1.4 PV penetration level in European countries

Figure 4 presents PV power penetration and energy coverage calculations based on a one year simulation with hourly load[1] and PV[2] profiles for the different European countries with the highest PV installed capacity (above 1% of the final consumption). All together, these countries represent 92 % of the current installed capacity in Europe.

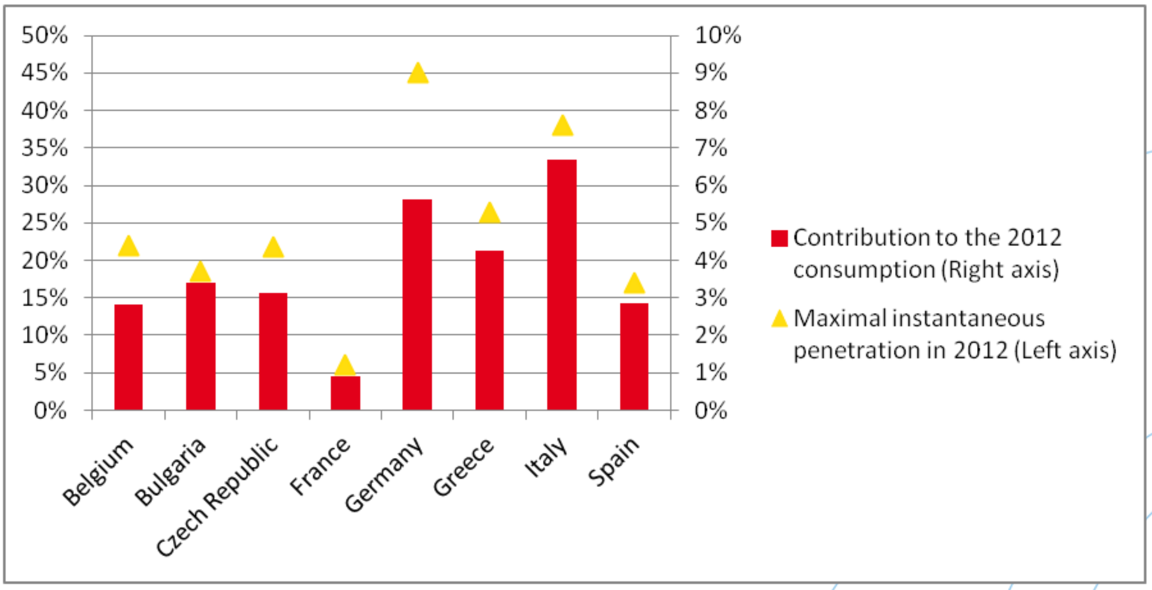

Figure 4 - Contribution to the final consumption and maximum instantaneous penetration. (source: ENTSO-E, EPIA, 3E, 2013)

The maximum instantaneous penetration level of PV is reaching high values in most of the countries with a maximum of 45% in Germany. Taking into account the spatial spread presented in Figure 2, it can be estimated that PV power in some European regions is reaching during the sunniest hours higher values than the demand. These regions are a showcase for large scale PV penetration. The know-how developed by distribution systems operators in these regions are the basis of the work conducted in the frame of the PV grid project and especially in WP3.

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[1] The times series are based on ENTSO-E 2012 data

[2] The times series used have been produced using national 2011 weather data and a pre-defined spatial spread of the installed capacity [11]

3.2 Czech Republic

In the Czech Republic, PV installations with an installed peak power below 100kWp are usually connected to the LV grid, installations up to approximately 5MWp are connected to the MV grid (mostly 22kV or 35kV), and only a few larger PV power plants are connected to the HV grid (110kV).

Power range in kWp	Number of installations	Total PV capacity in MWp
under 30	17779	1292
30-100	1370	29
100-300	615	30
300-2000	1581	275
2000-5000	550	326
above 5000	39	120

Table 2 - Statistics about PV size in Czech Republic in 2012 (Source: Energy regulatory office)

A total of 2072 MWp of PV power has been installed by the 31st of December 2012. The geographical location of the PV power plants in Czech Republic is indicated in Table 3. Nearly 50% of the PV installed power is located in the southern part of Bohemia and Moravia and another 25% is located in the central part of Bohemia and Moravia.

Geographical area	Region	Capacity per region in MW	Capacity per geographic area in	Capacity share per geographic area
Central Bohemia	Prague	19,9	263,2	12,7%
	Central	243,3		
Southwest Bohemia	South	244,2	455,2	21,9%
	Pilsen region	211,0		
Northwest Bohemia	Karlovy Vary	13,8	175,6	8,5%
	Usti region	161,8		
Northeast Bohemia	Liberec region	110,4	295,1	14,2%
	Hradec Kralove	89,1		
	Pardubice	95,6		
Southeast Moravia	Vysocina	88,1	553,1	26,7%
	South	465,0		
Central Moravia	Olomouc	110,7	271,6	13,1%
	Zlin region	160,9		
North Moravia	Moravian	58,2	58,2	2,8%

Table 3: Regional distribution of PV in the Czech Republic in 2012 (source: CZEPHO)

No significant voltage control issues linked to PV have been reported so far in the Czech distribution system.

3.3 Germany

In Germany, about 70% of the total PV capacity (usually PV plants with less than 100 kW) is installed in LV grids (Figure 5). The PV capacity in MV grid amounts for about 25%, which means that 95% of the PV capacity is installed in distribution grids.

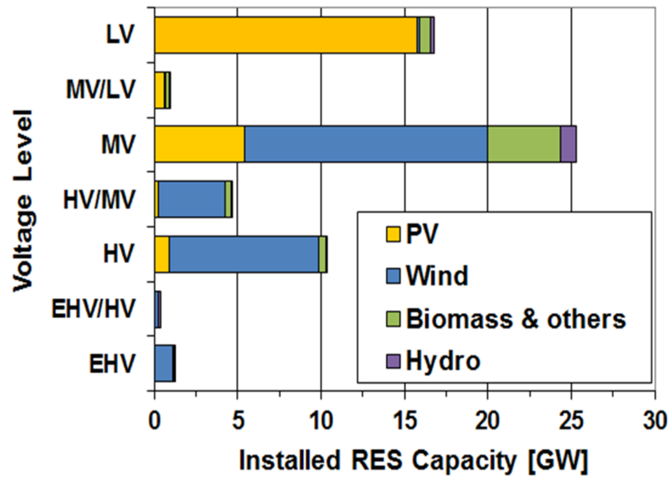


Figure 5 - Installed RES capacity per voltage level in Germany in 2011 (source: Fraunhofer IWES)

Bundesland	Number of instalations 2012	Total capacity MWp 2012
Deutschland	1.281.037	32.411
Bayern	412.371	9.642
Baden-Württemberg	244.828	4.272
Nordrhein-Westfalen	188.617	3.594
Niedersachsen	119.001	3.033
Brandenburg	23.807	2.515
Rheinland-Pfalz	74.431	1.545
Hessen	85.307	1.514
Sachsen-Anhalt	18.138	1.456
Sachsen	26.616	1.340
Schleswig-Holstein	30.969	1.220
Mecklenburg	11.199	964
Thüringen	18.735	882
Saarland	18.800	312
Berlin	4.561	61
Bremen	1.444	32
Hamburg	2.213	30

Table 4 – PV statistics for German regions in 2012 (source: BSW)

End of March 2013, the installed capacity of solar PV reached 33,409 GW (source: Bundesnetzagentur), with important regional differences as reflected in Table 4. Especially in the south of Germany in Bayern the PV capacity reaches the highest value with nearly 10 GW.

The contribution of PV in the 2012 German demand was 5 %. On the contrary, the PV power penetration level reached high values over 40 %, as on the 12.08.2012 (Figure 6) when about half of the German base load generation had to be exported to other European countries.

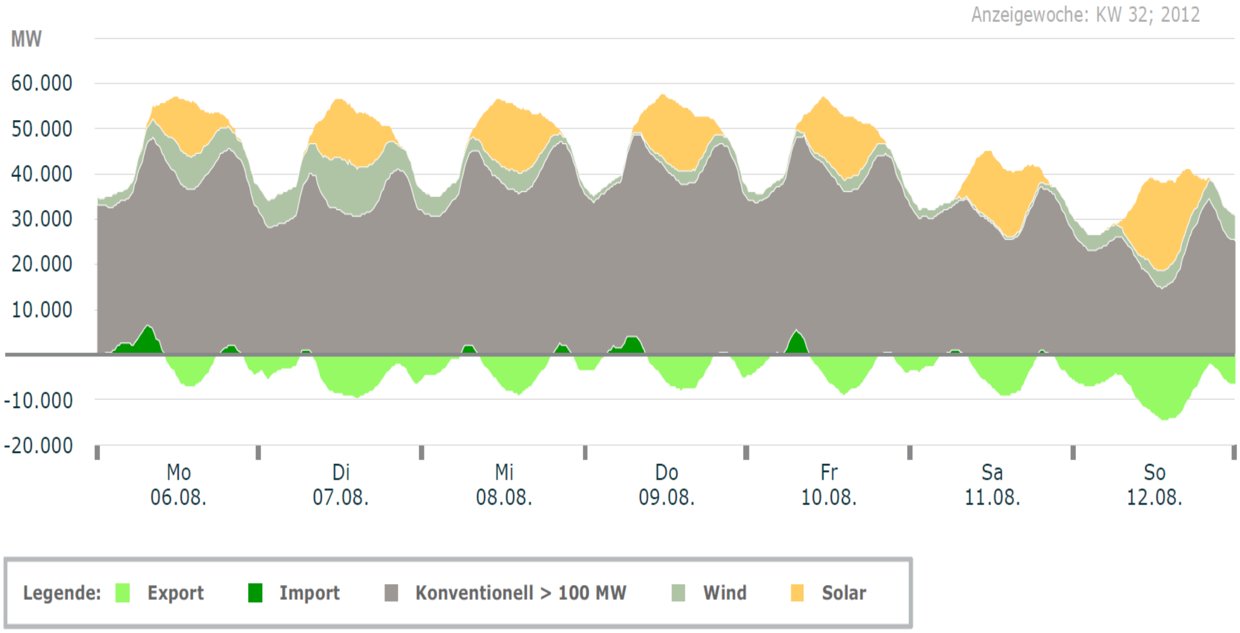


Figure 6 – Generation mix in Germany for the week 32 in 2012 (source: Fraunhofer ISE)

Such high PV power penetration levels induce very important reverse power flows in distribution grids, where the main challenges for DSO's are to maintain voltage quality within standards and to avoid possible congestions.

According to the recent Dena distribution grid study [8], the electricity grid infrastructure for transmission and distribution must be expanded in order to cope with the expansion of electricity generation from renewable energy sources. Electricity distribution grids in particular need expansion and conversion as most of the regenerative generation capacity is connected there.

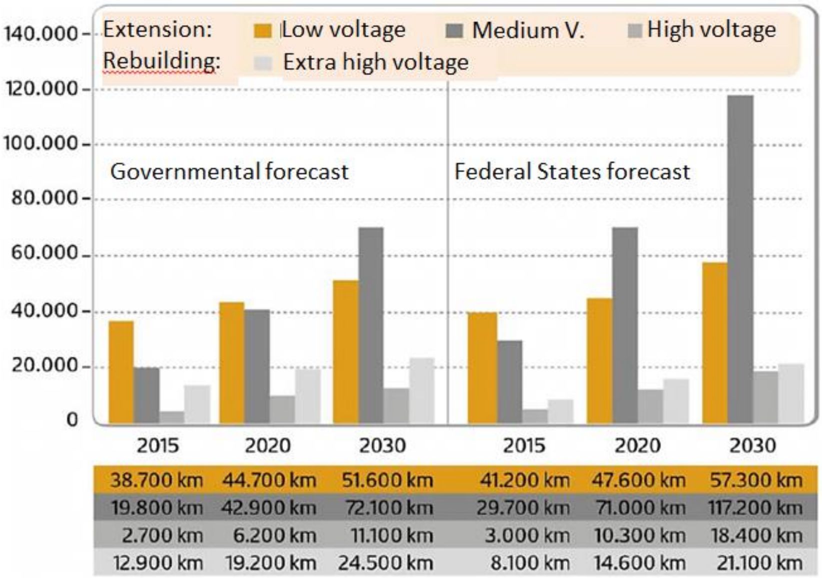
The Dena distribution grid study calculated the extent to which German distribution grids must be reinforced to integrate the electricity generated by renewable sources. Various expansion goals were assumed. In the first scenario, the expansion goals in accordance with guideline scenario B of the German grid development plan 2012 were assumed for transmission grids. The second scenario is based on the expansion goals of the German Federal States, which call for increased and faster expansion of onshore wind energy and PV. Both scenarios require the construction of new electricity lines and transformers at all distribution grid levels.

Results of Grid Development Plan 2012 scenario B:

- Grid expansion by 2030: 135,000 km
- Grid conversion by 2030: 25,000 km
- Investments by 2030: € 27.5 billion.

Results of the Federal States scenario:

- Grid expansion by 2030: 193,000 km
- Grid conversion by 2030: 21,000 km
- Investments by 2030: € 42.5 billion.



2015	2020	2030	2015	2020	2030
38.700 km	44.700 km	51.600 km	41.200 km	47.600 km	57.300 km
19.800 km	42.900 km	72.100 km	29.700 km	71.000 km	117.200 km
2.700 km	6.200 km	11.100 km	3.000 km	10.300 km	18.400 km
12.900 km	19.200 km	24.500 km	8.100 km	14.600 km	21.100 km

Figure 7 - Demand of grid extension and grid rebuilding in case the national or federal RES goals should be reached (source: DENA)

3.4 Italy

In Italy, in terms of total capacity installed the majority of DER installations is connected to the MV level of the distribution grid, and criticalities are limited to the cases where it is necessary to build new infrastructure connected to the HV grid, i.e. when DER generated power needs to be evacuated to the HV level due to insufficient load located close to DG. These criticalities usually also have an impact on the EHV transmission level. In the LV level instead, where in terms of number of installations the majority of DER systems are connected, criticalities may appear locally, but do not have a systematic nature and are normally addressed during the connection phase.

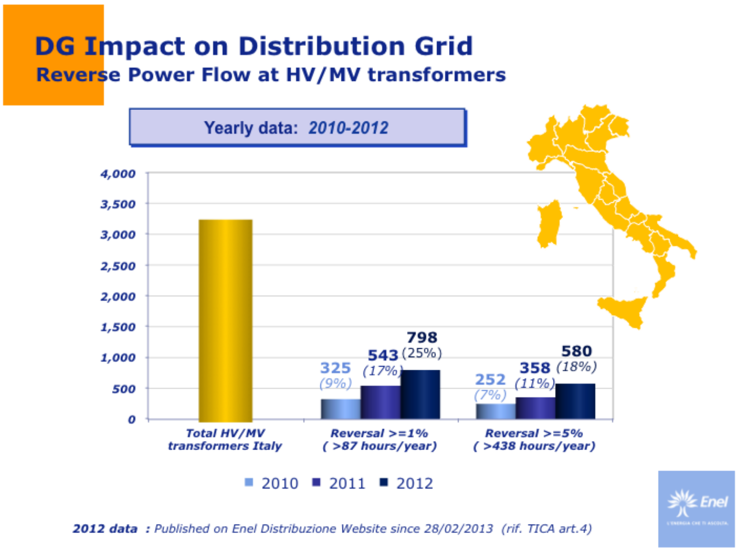
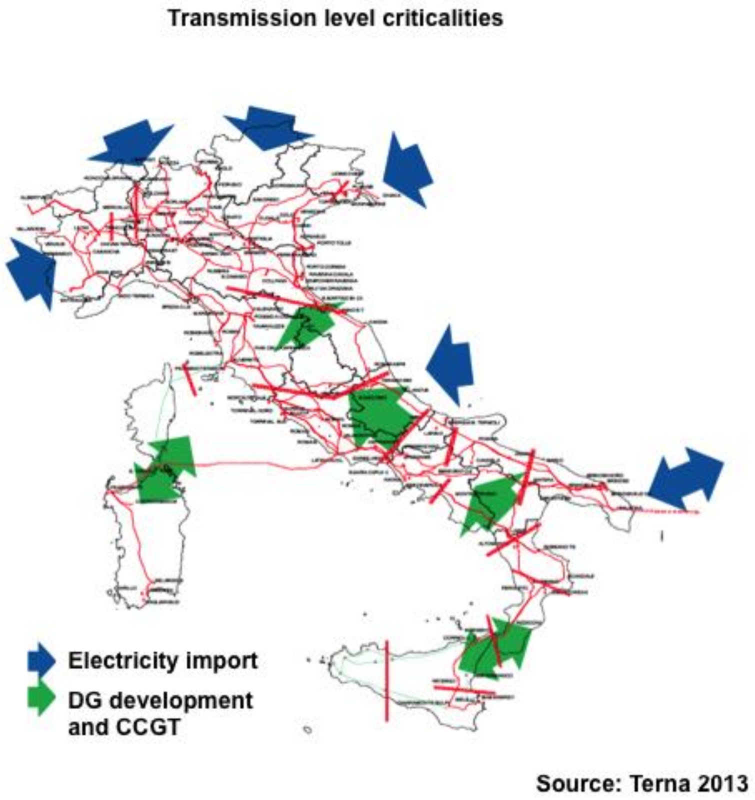


Figure 8 – Reverse power flow statistics in Italy for the period 2010-2012

As of 2012, the overall share of MV sections that need to evacuate power to the HV infrastructure for more than 5% of the time in a year have raised to 18% compared to 7% of 2010 (Source: Enel Distribuzione, representing over 85% of the Italian distribution market). However, this is only an overall national picture, while the regional picture varies wildly offering a more critical scenario in some areas.

On one side, there are regions like Lombardy, where conditions for DER are not favorable (densely populated, lower wind and solar resources) and load is high due to robust residential and industrial settlements. In such areas, no major issues are found. On the lower end of the boot, in southern regions like Apulia, Calabria and Sicily, where solar and wind resources are high and therefore DER is already largely deployed, scarce population and low industrialisation result in a low-medium local load. All these factors jointly contribute to a situation where, on a yearly basis, more power is injected from the MV to the HV grid infrastructure than vice versa.

In these critical areas, the DER hosting capacity is therefore either already saturated or virtually saturated, taking into account the DER capacity currently under development, and therefore costly and technically complex distribution infrastructure enhancement interventions are needed or under evaluation. Additionally, the needed upgrades on the HV infrastructure often trigger further interventions in the VHV infrastructure at transmission level, with a further negative impact on costs.


Transmission level criticalities

Source: Terna 2013

Figure 9 – Transmission level criticalities in Italy (source: Terna)

As a matter of fact, the Italian transmission infrastructure currently presents several criticalities linked to the evacuation of DER and traditional power generation facilities located in southern Italy towards the central and the northern parts of the country, while additional criticalities appear in the northern areas of the country, in this case linked to the import of electricity from neighbouring countries: France, Switzerland, Austria and Slovenia (source: Terna, Piano di Sviluppo 2013).

3.5 Spain

In Spain, most of the PV installations are connected to low voltage (less than 1 kV) and medium voltage (from 1kV to less than 36 kV) while the minority of them are connected to higher voltage (>=36 kV). A specificity of Spain is the significant contribution of solar thermal concentration power plants, which power might add to the PV production in peak hours if no thermal storage is available. As can be seen in Table 5, solar thermal plants are however much bigger in size and have a limited impact on distribution grids as they are usually connected to higher voltage levels.

	SOLAR PV			SOLAR THERMAL		
VOLTAGE RANGE	**Sold Energy (GWh)**	**Installed capacity (MW[3])**	**Number of installations**	**Sold Energy (GWh)**	**Installed capacity (MW)**	**Number of installations**
0<=U<1	2.854	1.608	34.158			
1<=U<36	3.855	2.138	19.570	418	241	7
36<=U<72,5	1.004	523	4.411	352	181	5
72,5<=U<145	271	142	855	418	280	6
145<=U<=400	147	81	771	2.243	1.249	25
Total	8.130	4.492	59.765	3.432	1.950	43

Table 5 - 2012 statistics for solar electricity in Spain

Compared to the Spanish electrical demand, PV production is still not significant. In 2012 the PV sector produced 3.2% of the demand. July 2012 was the best month in terms of coverage (4.2%) and the 27th of May, 2012 the daily record was 6%. Figure 10 indicates however that the PV energy coverage varies significantly between the different Spanish regions. In Castilla la Mancha and Extremadura, the PV energy coverage in 2011 reached respectively 13% and 22%. In the rest of Spain the ratios were around the 5%. The case of the Autonomous Community of Extremadura is particular because it is a large area region with a small population and demand, which is exporting a lot of its electricity production to the rest of the Spanish territory through a strong transmission grid.

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[3] For Spain, the installed capacity is expressed in MW_{AC} (not MW_{dc} like in the other countries).

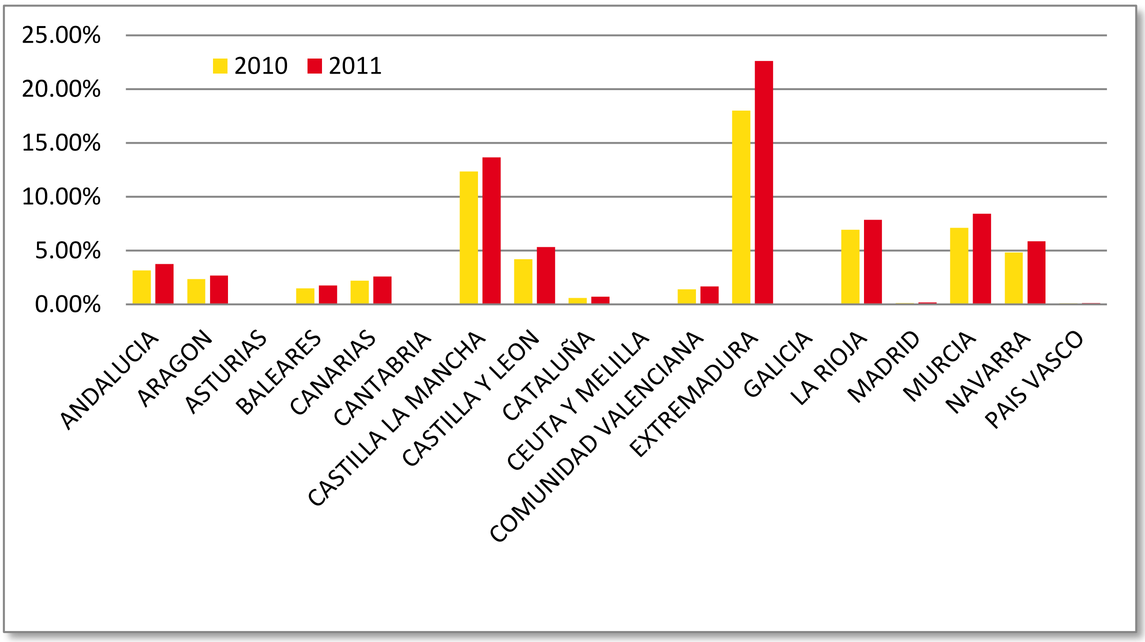

Figure 10 – PV coverage of the demand in 2010 and 2011 by Spanish regions (Source: UNEF)

Figure 11 indicates that the areas that have a deeper PV penetration are generally located close to high voltage lines for the evacuation of the power.

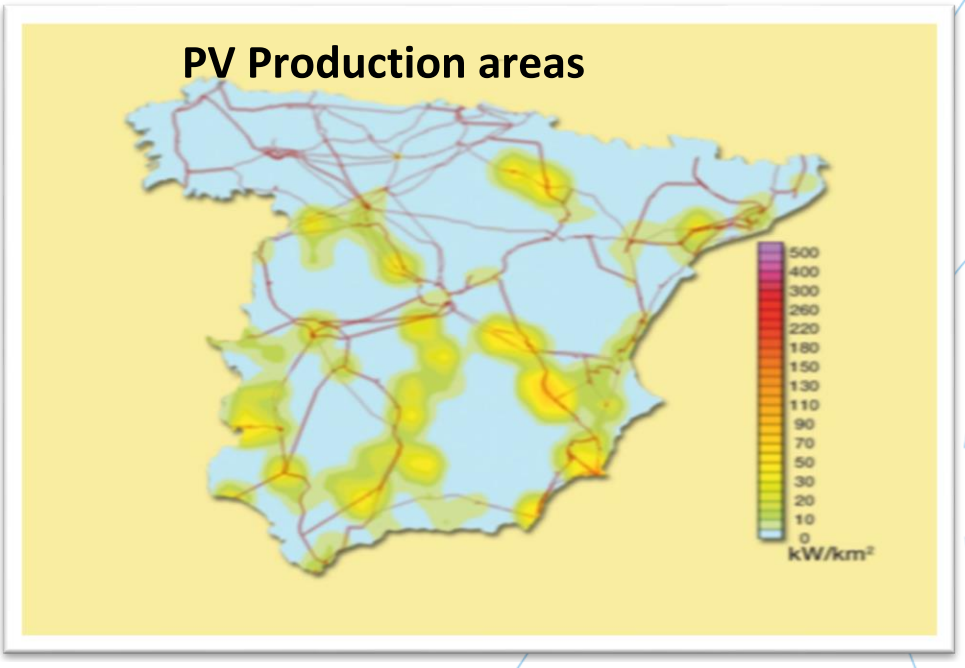

Figure 11 - PV production areas in Spain (Source: REE)

With a decrease of the demand and the increase of the PV generation, reverse power flows have intensified in the recent years mainly in the areas where power is consumed at different time than generated (E.g. in lines that feed night-time water irrigation bombs).

The associated common problems in the daily operation are those related to the voltage. Traditional voltage control methods based on HV/MV transformers with on load tap changer are not efficient anymore to control adequately the voltage in low and medium voltage networks with high reverse power flows due to distributed generation.

Due to the continuous network infrastructure improvement and adapted regulatory framework, Spanish electric system has not suffered from congestion problems.

4 TECHNICAL CHALLENGES FOR THE GRID INTEGRATION OF HIGH SHARES OF RENEWABLES

The massive increase of solar photovoltaic (and other intermittent renewable) power generation systems leads today in the European grid to new integration challenges in order to ensure the reliability and quality of the power supply. These new technical challenges for grid operators may delay the further enlargement of solar photovoltaic power generation if not taken into account. Several issues can be identified regarding the impact of high PV penetration on grid system operation as presented in the PV GRID discussion papers [1] [2] [3] [4] and in recent papers like [5]:

1) **Reverse power flows in the distribution system**: In distribution systems where the local PV generation exceeds the local load demand, reverse power flows occur toward higher voltage levels. This phenomenon is often accompanied in long feeders by voltage rises. Consequently, the allowed voltage band of +/-10% of the nominal voltage (according to the power-quality standard EN 50160 for slow voltage variations) is more often violated with PV than without PV. In areas with high load densities and shorter feeders, voltage violations might however not happen before excessive PV feed-in creates congestion by over-loading system components (feeder, transformer). Congestion can also be a problem in all regions where voltage issues are solved by any "smart solution" if DER capacity increases over a critical point.

2) **Additional power flows in the transmission system**: Reverse power flows can cause additional power flows from the distribution system to the transmission system and have an impact on power exchanges between TSO's areas, congestion at transmission level.

3) **Grid stability**: in the past, only conventional power plants had to guarantee the system's stability. Today, with increasing shares of DER generation, the DER systems' contribution to network stability becomes essential. This implies that even smaller photovoltaic systems connected to the distribution grid must fulfill requirements concerning frequency and voltage support. For example, in emergency situations leading to under-frequencies, it is crucial that distributed generation would continue to generate at maximum power. On the contrary, in case of over-frequencies, PV power should be curtailed progressively according to a smooth frequency ramp. However, the cutoff frequencies for RES still vary in Europe, which can cause instabilities in abnormal situations (e.g. the 50.2 Hz risk[4]). Another issue is the Voltage Ride Through capability of DER units. In the past grid connection conditions had intended to disconnect RES, when voltage dropped below a threshold. This had lead to the disconnection of a high percentage of generation even in case of very short voltage drops.

Dealing with all these aspects would require a full system picture also including the transmission grid level, which is out of the PV GRID project scope. Within the PV GRID project, only technical solutions able to mitigate the negative impacts of reverse power flows in distribution grids have been considered. Concerning the technical challenges caused by the integration of DER units into distribution grids, the major issue is to identify the cheapest solutions which guarantee to stay within the allowed voltage band and to avoid reaching the thermal limits of network assets. In the following sections, voltage control and congestion issues in low voltage grids are introduced.

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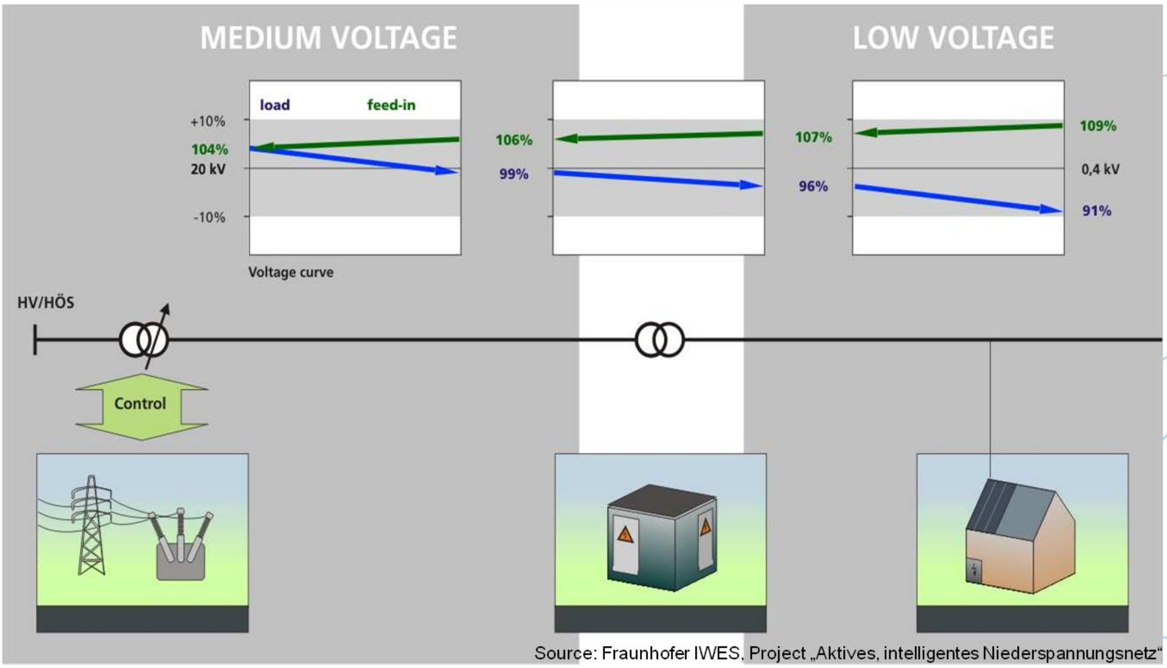
[4] The risk refers to Germany where generators connected to the low voltage distribution network before 2011 had a fixed cut-off frequency at 50.2Hz. Generally, without progressive curtailment, if the system frequency exceeds a fixed threshold at a point in time with high decentralized in-feed, power amounting to several gigawatts would be shut down in extreme cases. The resulting sudden power variation might be significantly higher than the primary control power defined Europe-wide, so that power frequency control could no longer stabilize the mains frequency. In addition, a more or less simultaneous re-connection of the decentralized generators in the course of a frequency recovery could lead to the frequency threshold (e.g. 50.2 Hz) being exceeded once more, thus causing the generators connected to the low voltage distribution network to shut down again ("yo-yo effect").

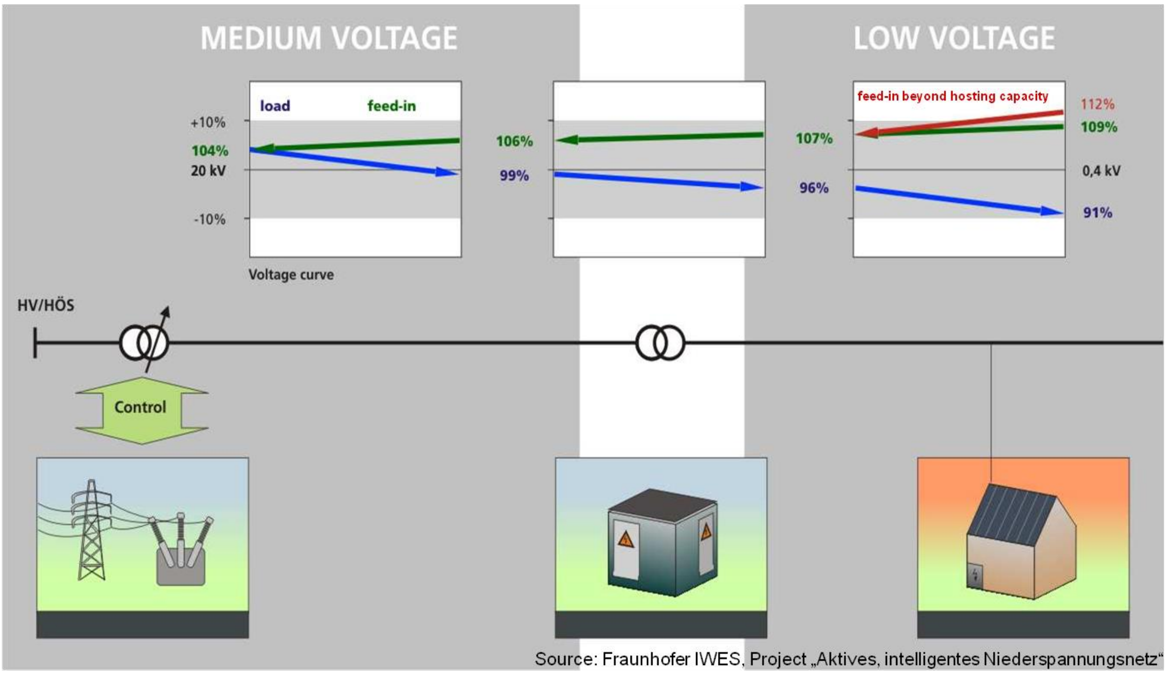
4.1 Voltage control in low voltage distribution networks

Concerning the integration of DER units into LV networks the current challenge is in most cases to stay within the allowed voltage band. Voltage parameters which have to remain within standards include both slow (voltage) variations, due to normal operation of PV systems, and fast (voltage) variations occurring in case of instantaneous disconnection of the newly-inserted PV. In the case of slow variations, Figure 12 shows extreme voltage profiles corresponding to a maximum load case (in blue) and to a maximum feed-in case (in green) starting at the substation between the transmission and the distribution grid, moving along the Medium Voltage (MV) feeder over the MV/LV transformer to the end of the low voltage (LV) feeder where the PV generator is connected. In the past distribution networks have been designed for the maximum load case. Nowadays the feed-in of distributed generation, mainly wind in MV and PV in LV, leads to a voltage rise within the distribution network. Only 2% in the MV network and 2-3% in the LV network are assigned to this voltage rise, although the available voltage tolerance band is ± 10%. This is a limiting factor for a further broad and fast expansion of distributed generation. If more PV is integrated in this LV feeder (Figure 13), the PV capacity might become greater than the grid hosting capacity, which means that in times of high PV generation and low demand, the existing control system at the HV/MV substation is not able to keep the voltage within the +/-10% band (red voltage profile). Different technical solutions are available in order to avoid costly network reinforcement and will be analyzed in the following sections of the report.



Source: Fraunhofer IWES, Project „Aktives, intelligentes Niederspannungsnetz“

Figure 12 – Voltage control in low voltage grids (PV capacity < grid hosting capacity) [7]



Source: Fraunhofer IWES, Project „Aktives, intelligentes Niederspannungsnetz“

Figure 13 – Voltage control in low voltage grids (PV capacity > grid hosting capacity) [7]

4.2 Congestion in distribution grids

The production pattern of PV systems, although variable, does not vary substantially from one system to another (generation always increases in the morning, reaches a peak around midday and decreases in the afternoon). Hence, around midday in regions with a high installed PV capacity, the grid witnesses a high pressure. In reality, due to the dependence to good DER-potentials and to the needed areas for the DER-installation, a local concentration of DER-generators occurs in rural areas with low demand density. If in these areas a high DER-based energy production meets a low demand it leads to a regional excess supply of energy which has to be transported to other regions. These power flows regionally exceed the existing power flows caused by the demand in these regions where the grid is dimensioned for historically. In these cases local overloading of the distribution grid occurs and can be conventionally solved by grid reinforcement. Grid reinforcement itself is usually a quite expensive solution to integrate DER. In the next section, alternative technologies are identified, which can be used to reach a regional balancing, to avoid extreme grid loading and to find more economic solutions than conventional grid reinforcement.

5 OVERVIEW OF MOST EFFECTIVE TECHNICAL SOLUTIONS SUPPORTING THE GRID INTEGRATION OF HIGHER SHARES OF PHOTOVOLTAICS

5.1 Methodology

For the purpose of assessing the state of the art, documents were collected by project partners. The sources for documents were mainly national, European and other international projects, grid codes and standards.

Two working groups have then been set up for the purpose of evaluating the documents:

- WG1: Discussion of technical issues and solutions on the network and consumer side.
- WG2: Discussion of technical issues and solutions on the PV system side

The initial findings of the working groups were detailed in two discussion papers ([1], [2]) which were the basis for consulting other stakeholders. Further to the stakeholders' consultation, the technical solutions variants and combinations were described more accurately and the list was refined in order to reach a large consensus between stakeholders.

5.2 List of technical solutions

Table 6 presents the list of technical solutions which potentially can increase the hosting capacity in distribution grids. As already mentioned, only the technical solutions having an impact on voltage quality and local congestion management have been considered in the remainder of this work.

As some of these technical solutions may be applied for both voltage quality and congestion management problems, it was decided to classify them according to the following 3 categories:

- **DSO** for solutions that are implemented within the grid operator infrastructure and require no communication with the consumer (or prosumer)
- **PROSUMER** for solutions which are implemented within the consumer (or prosumer) infrastructure and require no communication with the grid operator
- **INTERACTIVE** for solutions that are implemented within both the grid operator and the prosumer infrastructures and where the different components react based on signals exchanged via a communication infrastructure

The technical solutions are described in the following sections.

Category	#	Technical solution
DSO	1	Network Reinforcement
	2	On Load Tap Changer for MV/LV transformer
	3	Advanced voltage control for HV/MV transformer
	4	Static VAr Control
	5	DSO storage
	6	Booster Transformer
	7	Network Reconfiguration
	8	Advanced Closed-Loop Operation
PROSUMER	9	Prosumer storage
	10	Self-consumption by tariff incentives
	11	Curtailment of power feed-in at PCC
	12	Active power control by PV inverter P(U)
	13	Reactive power control by PV inverter Q(U) Q(P)
INTERACTIVE	14	Demand response by local price signals
	15	Demand response by market price signals
	16	SCADA + load control
	17	SCADA + PV inverter control (Q and P)
	18	Wide area voltage control

Table 6 - List of technical solutions

5.3 Description of technical solutions

5.3.1 Network Reinforcement

Network reinforcement is the more traditional action carried out in order to ensure compliance with voltage and thermal requirements in case the connection of a new PV plant may bring variations outside the standards. In specific situations, this solution might include building a new feeder (and eventually a new MV/LV substation) instead of reinforcing an existing one (if it's cheaper or more effective).

Technology availability

It is a simple solution, appropriate for voltage issues and congestions. It is usually simple in terms of permitting processes and does not take too much time in implementing. It is therefore the action most frequently adopted.

Implementation difficulty

Its main disadvantages are the relatively high costs and the difficulty to make a robust and efficient planning for this investment without exact knowledge on the further development of generation and load. For example, in rural areas, where the major inconvenience is the distance to substations, voltage problems appear before current limits are exceeded. In that case, the reinforcements improve the voltage profile, but at a higher cost compared to other possible solutions. It is important to notice that by solving the voltage problems with other solutions, congestions can appear even in these rural areas.

Effects on voltage variations

Through reinforcement the impedance of the feeder is reduced, which reduces the impact on voltage of PV feed-in. The action can be used to reduce both slow and fast voltage deviations.

Effects on congestions

Reinforcement has a positive impact on congestion if the components, which are operated close to their thermal rating, are upgraded.

Areas of impact

Reinforcement is used in MV and LV networks.

5.3.2 On Load Tap Changer for MV/LV transformer

An On Load Tap Changer (OLTC) device is able to adjust the lower voltage value of an energized transformer. OLTCs are and have been largely used in HV/MV transformers. In MV/LV transformers, tap changers are usually not automated and have to be parameterized manually based on information about the MV grid topology, the position of the substation in the MV feeder and expected LV load in the field.

Technology availability

Existing MV/LV transformers are however not equipped with OLTC, but due to the increasing needs of active voltage control in LV grids caused by the increasing amount of implemented DER in this grid level these components have been developed in the past years. Right now this equipment is available on the market and is successfully tested in prototype projects.

Implementation difficulty

The OLTC option should increase significantly the costs for MV/LV substations. Additionally, the substation energy losses would increase slightly for enabling the voltage control capability.

Effects on voltage variations

The impact on voltage control is high, especially if all the LV feeders of the concerned transformer are loaded the same way.

Effects on congestions

No impact on congestion

Areas of impact

This measure is beneficial in areas where voltage problems are dominant.

5.3.3 Advanced voltage control for HV/MV transformer

This solution includes new control methods for existing HV/MV transformers with already installed OLTC.

Through OLTC the output voltage of the transformer can be changed according to the value of some parameters: these parameters for HV/MV transformers are usually the voltage at the MV busbar and the HV/MV transformer load. In a condition of purely passive load in the MV grid these two parameters allow a sufficient estimation of the voltage drop along the feeders and consequently an effective regulation of the voltage itself, optimizing the voltage profile according to the overall load.

The presence of DER connected to MV feeders makes this regulation not anymore reliable, as the overall load is influenced by embedded generation just as well as passive consumers.

In order to benefit from OLTC it is not possible to rely only on measurement at the HV/MV transformer level anymore; OLTC must be combined with some advanced voltage regulation system by measurements within the MV and LV grid to get a better knowledge about the actual grid state.

Technology availability

Presently, prototype projects of these advanced voltage control systems are implemented to collect experiences for the optimal distribution of measurements and the parameterization of control algorithms.

Implementation difficulty

The main complication of this kind of solution lies in the need for extra measurement points and for the grid monitoring communication infrastructure.

Effects on voltage variations

The effectiveness of this solution highly depends on the load-generation distribution. If the voltage profiles highly differ from one feeder connected to the regulated busbar to another, the effectiveness of a control through the HV/MV OLTC is limited.

Effects on congestions

No impact on congestion.

Areas of impact

The impact is on the MV and LV grids fed by the HV/MV substation.

5.3.4 Static VAr Control

A Static VAR Compensator (SVC) is an electrical device that provides fast-acting reactive power in an electrical network under various system conditions.

In order to integrate higher values of DER, it is possible to reduce slow voltage deviations by installing capacitors in the points where the lowest voltage values are going to occur in high load-low generation conditions.

Capacitors or Static VAR Compensators in MV lines can usually be installed in existing substations, without complex activities. DER and loads may require different compensations at different hours, because DER makes the voltage rise while loads make the voltage decrease. Any compensation for DER should be dynamic.

Technology availability

Many commercial products are available.

Implementation difficulty

Installation of SVC outside substations is often necessary for an efficient compensation of voltage rises and is relatively expensive.

Effects on voltage variations

Depending on their location, SVC can reduce the negative impact on voltage caused by the active power injection. The voltage drop induced by the increase of the load due to the reactive component can balance, to some extent, the voltage rise due to PV generation.

Effects on congestions

The impact on congestion is very limited.

Areas of impact

Reactive compensation can be used to sustain voltage in a MV or LV distribution network. Reactive power contribution to voltage control in LV networks is smaller as the resistive part of the impedance is prevailing.

5.3.5 DSO storage

Static storage systems, although still very expensive and space consuming, are flexible tools and can be used for solving many problems in distribution grids. Typical applications are peak shaving, power shifting, ancillary services and backup in case of grid failure.

Technology availability

Different storage technologies are available on the market.

Implementation difficulty

High costs and associated losses.

Effects on voltage variations

In case of voltage problems, storage can benefit from the inverter's flexibility, which is part of storage systems, for reducing or increasing voltage along a feeder by absorbing or injecting power.

Effects on congestions

Congestion problems are solved by shaving the power injection peaks.

Areas of impact

Stand-alone storage system can be inserted within a MV or a LV feeder and their operation can be automatically controlled based on the voltage value at the point in which the storage system is connected to the network.

5.3.6 Booster Transformer

A Booster Transformer is a transformer of which one winding is intended to be connected in series with a feeder in order to alter its voltage and the other winding is an energizing winding. Boosters are MV-MV or LV-LV transformer that can be used to stabilize the voltage along a feeder. In the past, boosters have been generally installed in long feeders to compensate voltage drops exceeding standards. It can be imagined to use the same equipment for mitigating negative impacts of PV on voltage.

Technology availability

Different technologies of booster transformers are available on the market.

Implementation difficulty

The choice among possible solutions depends on the placement of load and generation along the feeder. However, it must be noted that:

- installing a booster along an existing feeder requires some work, which is not necessarily simpler or fastest than a more "conventional" reinforcement;
- the adequacy of a booster solution is not necessarily granted in case the load and generation distribution change in time.

Effects on voltage variations

In principle, two options are available:

- Voltage at MV (or LV) busbar is kept low in such a way that at maximum generation the voltage does not exceed standards and booster is used to compensate voltage drops in high load-low generation conditions;
- Voltage at MV (or LV) busbar is kept high in such a way that at minimum generation the voltage does not fall below standards and booster is used to reduce voltage in high generation-low load conditions.

Effects on congestions

No impact on congestion.

Areas of impact

It can be used in LV and MV grids.

5.3.7 Network Reconfiguration

Revising network switching state is a simple measure that may be applied in order to solve problems occurring from the connection of additional distributed generation (DG).

MV grids are usually topologically meshed, but operated radially. This means that in boundary points some switches are kept open and can be used for re-supplying the feeder in case of outages. The network configuration is always optimized for existing network conditions: in case of connection of a new DER plant or other significant changes within a feeder, it may happen that, by changing the substations that are used as boundary points a new configuration can be obtained which complies with all voltage requirements.

However, this solution has usually a quite low impact and should be considered only as an initial measure that can be applied in regions with rather low DER penetration.

Technology availability

This solution is state of the art and currently applied within grid planning and operation procedures.

Implementation difficulty

The reconfiguration is limited to areas and voltage levels where switching alternatives exist.

Effects on voltage variations

An adaption of the DER distribution in different feeders respecting the existing load distribution can help to reduce voltage variations.

Effects on congestion

An adaption of the DER distribution in different feeders respecting the existing load distribution can also help to reduce congestions.

Areas of impact

The effectiveness of this solution is limited due to the fact that balancing of load and DER in feeders is limited. A reconfiguration is limited to areas where at least ring or other meshed structures exist which are usually operated with open switches. Therefore, this measure is mainly relevant for MV grids and urban areas.

5.3.8 Advanced Closed-Loop Operation

Closed-Loop Operation (or Closed Ring Operation) is the method of grid operation where each point of a given part of a network is fed from two different sources along two distinct paths. Closed-Loop may be described as an operational practice in which, in a meshed topology, two feeders are jointly operated.

Technology availability

Meshed operation is the standard for HV networks, but it is an uncommon practice for MV ones with possible negative impacts on system reliability. Meshed operation has also been experienced in a very limited number of cases of LV grids (at least in Germany). Closed-loop operation is currently adopted in a few urban areas. Reliable closed-loop operation at MV level requires preferably a Smart Grid infrastructure with advanced protection schemes based on a reliable, bi-directional communication infrastructure (e.g. optical fibers) and remote control of switches within the grid.

Implementation difficulty

This solution can only be implemented in areas where a meshed grid infrastructure exists. In a meshed grid the area potentially influenced by a technical fault is larger which has a huge impact on the system reliability. To reduce the negative effects it is necessary to install reliable, bi-directional communication infrastructure and remote control in MV and LV grids i.e. this solution cannot be implemented without at least some additional investment by the DSO.

Effects on voltage variations

By closing the “boundary” switch between the two feeders the equivalent impedance of the circuit is reduced, thus reducing the voltage rise and both slow and fast voltage variations.

Effects on congestion

As DER and all remaining loads of different feeders are connected in these solutions a better balancing could be reached which can help to reduce congestions.

Areas of impact

The effectiveness of this solution is limited to areas where at least ring or other meshed structures exist which are usually operated with open switches. Therefore, this measure is mainly relevant for MV grids. Due to the high impact on system reliability it is necessary to combine this solution with additional communication, measurement and control technologies within the grids.

5.3.9 Prosumer storage

Although still very expensive, small decentralized storage systems can actively contribute to reducing local voltage deviation and congestion problems by peak shaving (reduction of the maximum load fed into the grid by DER i.e. grid feed-in power lower than PV generation power). In addition, storage can also be used for reducing the grid load at peak demand. Also a general advantage of (micro-)storage is that the customer does not need to change his behavior. The fluctuating generation is buffered by storage and can be used whenever needed.

Additionally, storage systems can be used to maximize the direct consumption of the DER power. Storage can help to shift the non-dispatchable energy of DER or cheap energy available within the electricity market to the time with high demand. Finally, prosumer storage may ease the fulfillment of production schedule.

The incentives for prosumer storage systems can be simply based on a (mandatory) self-consumption scheme. In a more sophisticated system, this solution could also be combined with an interactive solution (e.g. variable off-take tariffs i.e. by commodity price signals).

Technology availability

This solution is already available in the market. Most of the existing products focus on small residential DER. Nevertheless, the market is currently developing additional products to fulfill the requirements of all DER sizes.

Implementation difficulty

While the technical solution is already in the market the financial incentives for these systems are difficult to implement. The prosumer himself who should install the system has only limited economic benefits by increasing the self-consumption. Additional benefits like for possible reduced grid infrastructure costs have to be brought to the investor by e. g. subsidies. Albeit increasing production numbers might lead to a situation where economy of scales can be realized in the future and (micro-)storage becomes more competitive.

For the general optimization of storage benefits it is necessary to implement rules for the storage operation deciding whether a local peak shaving should be organized or the general balancing within the electricity system should be supported. These operational schemes can differ in several points of time and might actually involve a conflict between different optimization approaches. In any case, it should be avoided to increase the grid load by uncontrolled centralized operational signals. Therefore, a communication between DSO and the storage operator is necessary if the storage has to be dispatched following a market signal. More information about the design of such a market can be found in [12].

It has to be mentioned that if increasing self-consumption of prosumers might help to reduce grid expansion costs, in this case less energy will also be transferred via public grids which might cause an increase of grid tariffs for the remaining customers.

Effects on voltage variations

The installation of storage systems with a grid oriented operation scheme like peak shaving has very similar effects to those borne by an increased decentralized consumption which helps to avoid voltage rise.

Effects on congestion

The installation of storage systems with a grid oriented operation scheme like peak shaving has very similar effects to those borne by an increased decentralized consumption which reduces the grid load.

Areas of impact

Prosumer storages are mainly interesting in areas where the DER is located next to comparable loads. This is especially the case for residential implementation of PV i.e. in LV grids. In areas with a high implementation of small DER this solution can also cause benefits within higher grid levels.

5.3.10 Self-consumption by tariff incentives

An adequate measure to reduce the distribution grid load is to set up explicit incentives for the self-consumption by the prosumers. The prosumer can optimize his own demand in relation to the fluctuating DER in his household. The benefit of such an incentive scheme is that the prosumer is able to decide by himself whether he wants to adapt his demand or not. No additional direct external control signals are needed which means that communication infrastructure is not needed for this solution. Self-consumption is a special kind of demand response without external signals. If the prosumer’s demand is not flexible enough, he could decide to install a “prosumer storage” system (solution 9 in the list) to make his own generated energy available when needed. Residential energy information and management systems can be beneficial here from the prosumer’s point of view as they help in the optimization process.

Self-consumption reduces the load of power grids in two respects: energy that is consumed at the same location where it is generated no longer has to be transported over the grid. In addition, energy needed for consumption does not have to be purchased via the public power grid. If grid parity is achieved, electricity produced is cheaper than electricity taken from the grid and self-consumption does not need specific incentives unless an unsuitable too high feed-in tariff exists (i.e. feed-in tariff > price of grid take off > production cost). If this is not the case the cost of solar energy is equal to or less than the cost of conventional energy and it is profitable for each PV prosumer to use as much self-generated PV energy as possible.

Technology availability

Different products to support a residential energy management are in the market.

Implementation difficulty

Due to the fact that the prosumer can decide by himself whether he wants to increase the self-consumption (based on an incentive or not), the DSO must consider for its grid planning the risk associated to the stochastic nature of consumer behavior. Although this risk can be statistically mitigated by a large number of prosumers, it is expected that a fixed limitation of the maximum power feed-in at the point of common coupling (solution 11 in the list) has a higher potential for reducing grid expansion costs. It should also be mentioned that this solution works only with prosumers that are aware of the overall problem. As described for prosumer storage (solution 9) it has to be mentioned that increased self-consumption influences also the grid tariffs for the remaining customers.

Effects on voltage variations

Decentralized consumption helps to reduce the load within the public grid and therefore also the voltage rise, but can be only considered within the grid planning if the reduction is reliable.

Effects on congestion

Decentralized consumption helps to reduce the load within the public grid and therefore also the grid congestions, but can be only considered within the grid planning if the reduction is reliable.

Areas of impact

Self-consumption is mainly interesting in areas where DER is located next to comparable loads. This is especially the case in LV grids with residential and commercial implementation of PV. In areas with a high implementation of small DER the solution can also cause benefits within higher grid levels. It would also be desirable that the DER produces in the same hours than the load. For example, watering loads in the night and PV production would not be beneficial, but instead would cause further voltage problems.

5.3.11 Curtailment of power feed-in at PCC

In this solution, the prosumer is responsible for not exceeding an agreed limit for the power fed into the public grid either by using a dump load or by reducing its PV peak production. Technically, the meter at the customer’s site measures the active power feed-in at the point of common coupling (PCC) and controls that the feed-in power is never above the contracted maximum power or above a fixed value (e.g. 70% of the installed PV capacity as implemented in the German Renewable Energy Act for new PV installations under 30 kW). Fixed curtailment makes sense as the real production of a PV system only seldom reaches values that are close to its installed capacity. It should be noticed that even a significant reduction of the generated power (kW) causes only a small loss of energy production (kWh) [11]. This correlation can be explained by the generally fluctuating nature of PV generation. This solution complements the self-consumption by tariff incentives (solution 10 in the list), which is based on the voluntary involvement of the consumer and is therefore less reliable. Alternatively, the active power at the PCC could also be limited by the DSO itself only in critical situations, which would reduce energy curtailment to a minimum, but would require additional bi-directional communication technology as described in solution 17. Both solutions enable an additional implementation of DER which can increase the degree of utilization of the public grid.

Technology availability

This solution can be technically implemented in the system based on existing equipment like smart meters, residential energy management systems and inverters which are able to curtail generation.

Implementation difficulty

To ensure a reliable peak power reduction it is necessary to have technical means to control it e. g. by smart meters at PCC of prosumers sites. Moreover, if the prosumer wants to try not to lose energy, an energy management system has probably to be installed within his/her premises for activating flexible loads, which implies an extra cost. The prosumer might even be compensated for the reduction of generated energy of the DER and the corresponding loss of income as long as the advantages/savings are actually larger than the lost (opportunity) cost for the consumer. However, today in many countries the DSOs are not allowed to optimize between the grid expansion costs and an economically compensated DER curtailment. Especially such a curtailment is potentially in conflict with the RES Directive rules on privileged connection and priority access rules for PV and RES in general[5] (transposed as cf. “Einspeisevorrang”/ unlimited feed-in priority in Germany). It is important to notice that this innovative curtailment solution implies that a portion of the PV power (the one causing congestion and voltage issues) is no longer given priority access. Some members of the PV Grid consortium have conducted analyses showing that this solution might represent the only way to keep a partial “priority access” without discriminating between previously installed DER and new DER.

Effects on voltage variations

A reduction of feed-in peaks at the prosumer’s PCC is a valid measure to reduce voltage rise within LV grids because of the given R/X ratio.

Effects on congestion

A reduction of feed-in peaks at the prosumer’s PCC is a valid measure to reduce congestions within distribution grids.

Areas of impact

This solution is effective for all voltage levels.

5.3.12 Active power control by PV inverter P(U)

Voltage and congestion problems can be solved by curtailing the PV feed-in power. For economic reasons, active power reduction should be used only when all other less expensive solutions have been applied. However, if overvoltages occur in LV grids that cannot be reduced by other measures, it is better to reduce the power than to shut off completely the PV inverter. Contrary to the fixed active power curtailment as described in solution 11, it is possible to use the LV grid voltage as an indicator for the grid situation. The PV curtailment level is then controlled as a function of the voltage value.

Technology availability

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[5] The RES Directive stipulates that :

1) To the extent required by the objectives set out in the Directive, the **connection** of new RE installations should be allowed as soon as possible. In order to accelerate grid connection procedures, Member States may provide for priority connection or reserved connection capacities for new installations producing electricity from renewable energy sources (recital (61)).
2) Priority access and guaranteed **access** for electricity from RES are important for integrating RES into the internal market in electricity. Priority access to the grid provides an assurance given to connected RES-E generators that they will be able to sell and transmit the RES-E in accordance with connection rules at all times, whenever the source becomes available. In the event that the RES-E is integrated into the spot market, guaranteed access ensures that all electricity sold and supported obtains access to the grid, allowing the use of a maximum amount of RES-E from installations connected to the grid (recital (60)). Member States shall also provide for either priority access or guaranteed access to the grid-system of RES-E (article 16,1,(b)).

The solution is technically feasible, but an optimal parameterization for a P(U) control is not existing right now. Additionally, the coordination with other solutions to regulate the voltage in LV grids should be clarified.

Implementation difficulty

P(U) functions could be implemented as a last option to ensure grid voltage quality. The value of the lost energy should therefore not exceed the grid expansion costs. P(U) function could induce a kind of discriminatory treatment for the prosumers depending on the location of their grid connection which should be avoided. As in the solution discussed before, a wide-spread introduction of active power control by PV inverter is most probably in conflict with the RES Directive rules on “privileged” connection and priority access for PV systems and RES in general(transposed as cf. “Einspeisevorrang”/ unlimited feed- in priority in Germany). It is important to notice that this innovative curtailment rule implies that a portion of PV power (the one causing voltage and congestion problems) is no longer given a priority access. As mentioned above, some members of the PV Grid consortium have conducted analyses showing that this rule might actually represent the only way to keep a partial “priority access” without discriminating between older DER (which connected early) and newer DER (which connects only later).

Effects on voltage variations

P(U) control is an additional measure to avoid critical voltage rise.

Effects on congestion

Due to the fact that P(U) control is triggered by the grid voltage it is not a direct measure to compensate congestion problems. Nevertheless, in situations where voltage and congestion problems occur at the same point in time, the solution helps to solve both.

Areas of impact

Controlling the voltage level with a P(U) function is efficient for feeders with a predominantly resistive impedance, as it is the case in low voltage grids. This solution is therefore limited to LV grids.

5.3.13 Reactive power control by PV inverter Q(U) Q(P)

PV inverters are capable to provide reactive power (Q) as well as active power (P). It is therefore possible to require to an inverter to behave in a specific way in relation with reactive power, according to the voltage at the connection point or to the active power injected. With this solution, the reactive power of the inverter can be a function of its active power production [Q=Q(P)] or a function of local voltage measurements [Q=Q(U)].

Technology availability

This solution is currently available from a technical point of view.

Implementation difficulty

As the reactive power control by PV inverter is a stand-alone solution based on local voltage or internal active power measurements, no major difficulties can be foreseen. The characteristics of the Q=Q(x) function must be appropriately selected in order to maximize the effects of the control.

Effects on voltage variations

By modulating the reactive power exchange, PV inverters can reduce the negative impact on voltage caused by the active power injection; the voltage drop induced by the increase of the load due to the reactive component can balance, to some extent, the voltage rise.

Q(U) behavior implies PV inverter’s contribution is asked no matter the active power injected, Q(P) behavior assumes the PV contribution is given according to the operation of the generation plant.

Q(U) and Q(P) functionalities for PV inverters may help in case of slow voltage variations, cannot contribute in case of fast voltage variations (e.g. in case of sudden disconnection of a single generating unit).

Effects on congestion

Q(U) and Q(P) may only incidentally help in case of congestion. However, active power production of a PV plant and local voltage measurements do not necessarily give any evidence of a condition of network congestion. Furthermore, it is very unlikely that a Q(x) function which has been established to benefit in case of voltage variation may also positively affect the network in case of congestion.

Areas of impact

The effectiveness of this solution on managing voltage ultimately depends on the impedance of the feeder and is lower in case of high R/X ratio. This technical solution is therefore more effective in MV networks than in LV ones.

5.3.14 Demand response by local price signals

Demand response can be triggered by price signals in local markets to reduce the grid load in expected high load situations. These price signals can be set directly by the DSO or indirectly by energy aggregators, based on the estimated grid situation respecting demand and generation forecasts. In this approach, different electricity price areas are defined within the DSO network according to the grid loading. More information about the design options for such a market is available in [12].

This solution requires the installation of a smart prosumer energy interface (smart meter) able to receive the variable price signals, as well as a smart network information and control system (smart SCADA) on the DSO side and a communication infrastructure between them. In addition, home automation devices (or energy management systems) that take into account simultaneously the customer preferences and the prices are recommended.

Technology availability

This solution is potentially feasible and can be implemented in selected portions of existing networks.

Implementation difficulty

The main complication of this solution, like most interactive ones, lies in the need for a communication infrastructure. Measurement points, however dispersed, only require discrete installations, while communication implies covering the distances between all those installations in a way which is reliable enough to ensure near real-time data exchange.

Also parameterization is difficult for DSO because of fluctuating prices within the wholesale market. Objective incentives have to be set, but no usable methodologies currently exist. Additionally, it has to be ensured that customers are not discriminated by regional prices.

Effects on voltage variations

Reducing the energy consumption in case of peak load and increasing consumption in case of peak generation, as well as the complementary behaviors on the generation side, can help in case of slow voltage variations. No contribution can be expected in case of fast voltage variations.

Price signals do not necessarily achieve the desired effects in terms of behaviors as the adoption of corrective measures by the prosumer is on a voluntary basis.

As this technical solution needs some equipment which is shared with other more “deterministic” solutions, it can be adopted as a “first step” of a more complex control strategy.

Effects on congestions

In case demand response is based on voltage measurements in the connection points, it cannot be expected this solution bringing a significant contribution in the reduction of congestions. In case also load measurement along the feeder are implemented, making the system much more complicated, some benefits can be achieved in terms of management of congestions.

Also in this case, price signals on a voluntary basis do not guarantee the desired effects.

Areas of impact

In principle, demand response can be applied both in MV and LV networks with comparable results. However, implementing interactive measures on LV grids implies a larger number of installation points, resulting in an increased level of complexity of the system while the per unit size of installation is smaller. This measure is more suitable for areas with high density of flexible loads which can change their instantaneous consumption with few implications such as air conditioning and fridges.

5.3.15 Demand response by market price signals

Demand response can be triggered by electricity market price signals to reduce the grid load in expected high load situations. This solution requires the installation of a smart prosumer energy interface (smart meter) able to receive the variable price signals. Different implementations are possible for prosumer load control ranging from full automatic control by the energy interface to manual control.

However, having a global price signal which is the same for all prosumers will not allow discrimination between the different local situations in the distribution grid. It is indeed necessary to ensure that this price signal does not cause grid voltage quality or congestion issues in areas with low DER-generation. A global market price signal should even change the demand in cities where the DER-share is according to experience quite low. The resulting increased concomitance of the demand could also lead to grid congestion problems in these areas.

Technology availability

This solution is potentially feasible and can be implemented in selected portions of existing networks.

Implementation difficulty

The performances of a communication infrastructure to support demand response by market price signals are less challenging than those for local price signals: in case of predictability of daily load conditions, a single daily access may be sufficient, requiring a low-performance communication solution.

Effects on voltage variations

Reducing the energy consumption in case of peak load and increasing consumption in case of peak generation, as well as the complementary behaviors on the generation side, can help in case of slow voltage variations. No contribution can be expected in case of fast voltage variations.

However it is very unlikely that global system conditions, which lead to the energy price in electricity markets, match with local critical situations. Furthermore, price signals do not necessarily achieve the desired effects in terms of behaviors as the adoption of corrective measures by the prosumer is on a voluntary basis.

Therefore no significant contribution can be expected from this solution.

Effects on congestions

The same argument apply as in the case of voltage variations: it is very unlikely that global system conditions, which lead to the energy price in electricity markets, match with local critical situations. Furthermore, price signals do not necessarily achieve the desired effects in terms of behaviors as the adoption of corrective measures by the prosumer is on a voluntary basis.

No significant contribution can be expected from this solution.

Areas of impact

Market price signals are related to general system conditions. Therefore effectiveness of this solution can be expected being slightly greater as the system becomes bigger, i.e. in MV networks.

5.3.16 SCADA + direct load control

An alternative to demand response is the direct load control by a DSO (or by an energy aggregator) that could be relevant in critical grid situation. A capacity payment would be offered to the customers to get this flexibility in emergency cases. This solution requires smart meters being managed by the SCADA.

Technology availability

This solution is potentially feasible, from a mere technical point of view, and can be implemented in selected portions of existing networks.

Implementation difficulty

The main complication of this kind of solution, as already mentioned before, lies in the need for a communication infrastructure. In this case the need of interaction with Smart Meters may imply to upgrade the existing Smart Meter management system.

Effects on voltage variations

Reducing the energy consumption in case of peak load and increasing consumption in case of peak generation can help in case of slow voltage variations. No contribution can be expected in case of fast voltage variations.

Effects on congestions

In case the load control is based only on voltage measurements in the connection points, it cannot be expected this solution bringing a significant contribution in the reduction of congestions. In case also load measurement along the feeder are implemented, making the system much more complicated, some benefits can be achieved in terms of management of congestions.

Areas of impact

In principle, direct load control can be applied both in MV and LV networks with comparable results. However, implementing interactive measures on LV grids implies a larger number of installation points, resulting in an increased level of complexity of the system while the relative size of installation is smaller.

5.3.17 SCADA + PV inverter control (Q and P)

Voltage control and congestion management can be optimally performed by coordinating the active and reactive power delivery of all or only a set of PV inverters located in the same grid area. In order to effectively manage the grid, monitoring devices (sensors) must be installed also along the feeder. If sensors recognize deviations potentially exceeding the limits, actions can be taken by controlling the PV reactive power.

In situations of DER peak generation, an active power reduction can also help to avoid grid congestions. Nevertheless, a reliable active power control should not lead to energy losses of the PV generators that exceed the reduced grid reinforcement costs.

Technology availability

This solution is potentially feasible, from a mere technological point of view, and can be implemented in selected portions of existing networks. The more sophisticated the sensors’ requirements, the less adequate (from the techno-economic point of view) they are for LV networks.

Implementation difficulty

The main complication of this kind of solution, as already mentioned before, lies in the need for a communication infrastructure. In this case the interacting points are defined along the feeder and are not necessarily limited to prosumers’ connection points, and may imply a more complex architecture.

Effects on voltage variations

Acting on reactive and (more rarely) on active power injected by PV inverter can help in case of slow voltage variations. The effectiveness of this solution (compared, for instance, to stand-alone ones) is higher, provided location of sensors is appropriate, system response is adequate in terms of time of reaction and control functions are properly set. No contribution can be expected in case of fast voltage variations.

Effects on congestions

The availability of load measurements along the feeder can lead to benefits in terms of reducing congestion phenomena, provided the control system is sophisticated enough.

Areas of impact

In principle, PV inverter direct control can be applied both in MV and LV networks with comparable results. However, implementing interactive measures on LV grids implies a larger number of installation points, resulting in an increased level of complexity of the system while the per unit size of installation is smaller.

5.3.18 Wide area voltage control

This solution includes all Voltage and VAR control technologies available in the distribution grid, combined to efficiently monitor power, determine control settings, and then adjust voltage and reactive power. Equipment like Transformer OLTCs, Distribution capacitor banks, Distribution voltage regulators or PV inverters are coordinated to optimize voltage and power factor in the whole DSO area. Smart grid technologies are applied to enable measuring the voltage and power factor at several points, controlling the equipment, coordinating and optimizing the generation and load:

- Substation voltage and current sensors (including CTs/VTs)
- Distribution voltage and current sensors (possibly included in PV inverters)
- SCADA to collect readings back to central location
- Smart meters with bi-directional communications to central location
- Control packages for transformer load tap changers (OLTCs)
- Control packages for capacitors and other voltage regulators
- Distribution management systems, forecasting tools.

Technology availability

Although most of the components which are required to implement this solution are technologically available, putting in place all of them requires a huge additional integration effort.

Implementation difficulty

Installing a wide area control system implies a proper coordination of all the individual installations that can be used to solve voltage criticalities. This makes this solution one of the most difficult to implement, resulting in a full “Smart grid”, i.e. a very versatile solution able to approach a wide range of network conditions. However, the need of increasing the hosting capacity of an existing network in order to accommodate more PV cannot generally justify *per se* such a huge effort.

Effects on voltage variations

Being able to use in a coordinate manner all the devices which can individually be used to affect and correct voltage criticalities ensures the best results, as far as slow voltage variations are implied. No contribution can be expected to solve fast voltage variations.

Effects on congestions

Being able to use in a coordinate manner all the devices which can individually be used to solve congestion issues ensures the best results. Of course in case of conflicting objectives (voltage vs congestion) a hierarchy must be defined.

Areas of impact

In principle, wide area control can be applied both in MV and LV networks with comparable results. However, implementing interactive measures on LV grids implies a larger number of installation points, resulting in an increased level of complexity of the system while the per unit size of installation is smaller.

6 EVALUATION OF THE MOST RELEVANT TECHNICAL SOLUTIONS ALLOWING THE GRID INTEGRATION OF HIGH SHARES OF PHOTOVOLTAICS

6.1 Objective

In the previous section, different possible technical solutions have been identified for increasing the grid hosting capacity.

The objective in this section is to define a list of most wanted technical solutions at European level, by involving the expertise of distribution grid operators (DSOs), PV associations and other stakeholders.

These results are the basis for the further investigation of normative and regulatory actions that will allow a swifter and more economical implementation of the most promising technical solutions.

6.2 Methodology

6.2.1 Multi-criteria analysis and stakeholder dialogue

Due to the many different situations in the European distribution grids (PV penetration level, feeder characteristics, load profile, load density, …), comparing the benefits and costs of the different possible technical solutions for increasing the grid hosting capacity for PV, is not an easy task.

An initially foreseen approach to the prioritisation of the technical solution was to perform simulations on generic representative distribution grids for the 4 focus countries – Germany, Spain, Italy and Czech Republic. However, the assessment of the effort and resources necessary for this solution lead to the decision that the simulations' performing effort cannot be achieved within the activities of the PV GRID project. For further limiting the complexity, the consortium decided to keep the estimation of the operational costs (from PV owner side and DSO side) outside of the scope of the evaluation.

Taking into account the aforementioned considerations, it was decided to apply an iterative method based on a multi-criteria analysis, complemented by multi-stakeholder workshops.

Initially, the different technical solutions have been evaluated with some common criteria (cost, technology readiness, impact on grid PV hosting capacity, applicability within existing regulations) for four grid type categories (rural LV, suburban LV, rural MV and suburban MV grids) in each of the four focus countries.

In a second step, two multi-criteria indicators have been defined for assessing both the cost-benefit and the regulatory priority for each solution. The cost-benefit indicator is based on the three criteria cost, impact on voltage and impact on congestion. The regulatory priority indicator is based on two criteria: technology readiness and applicability within existing regulations. During the evaluation process, the distinction between rural and suburban grids was evaluated as not very relevant and only two grid categories (LV and MV) were kept.

Finally, the results for the different countries have been combined for defining a list with three effectiveness levels (high, medium and low) of technical solutions at European level for two grid types (LV and MV), by involving the expertise of distribution grid operators (DSOs), PV associations and other stakeholders.

6.2.2 Initial National Assessment by DSOs

The DSOs participating in PV GRID (RWE, ENEL, LUMEN), supported by Comillas and Iberdrola for Spain, have provided a national assessment of the implementation of each of the technical solutions in 4 different types of grids (LV rural, LV suburban, MV rural, MV suburban) by filling several evaluation tables in an Excel template. The evaluation was done according to five criteria described in Table 7.

Criteria/score	**1**	**2**	**3**	**4**	**5**
Investment cost	Virtually no cost	Low cost	Average cost	High cost	Very high cost
Technology readiness	Commercial product	Successful in pilot grid demonstration	Successful in the laboratory	Early research	Only concepts are available
Impact on voltage quality and reproducibility	Can solve any voltage deviation problem through appropriate sizing AND Can be applied in any location of the related grid category	Can solve many voltage deviation problems through appropriate sizing AND Can be applied in many locations	Can solve many voltage deviation problems through appropriate sizing AND Can be applied in a limited number of locations	Can solve only limited number of voltage deviation problems AND Can be applied in a limited number of locations	Nearly useless or not reproducible
Impact on congestion and reproducibility	Can solve any congestion problem through appropriate sizing AND Can be applied in any location of the related grid category	Can solve many congestion problems through appropriate sizing AND Can be applied in many locations	Can solve many congestion problems through appropriate sizing AND Can be applied in a limited number of locations	Can solve only limited number of congestion problems AND Can be applied in a limited number of locations	Nearly useless or not reproducible
Applicable within existing regulations	Can be done by any operator	Do not know	Do not know	Do not know	Requires change in regulation

Table 7 – Evaluation assessment criteria

The results of this process are the sixteen technical solution evaluation tables (four countries for four grid types) contained in [4].

6.2.3 Performance Indicators

Based on the evaluation results with the different criteria, 2 performance indicators were calculated for each solution in each table:

- **Techno-economic indicator,** which indicates the cost and benefits of a technical solution. It is the weighted sum of the three criteria investment cost (40%), impact on voltage (40%) and impact on congestion (20%). As grid hosting capacity limitations are usually linked with voltage problems, a higher weight is put on this criterion.

- **Regulatory priority indicator**, which indicates if the implementation of a technical solution is facing a regulatory barrier and how urgent it is to remove this regulatory barrier. This index is defined as in Table 8 with the following score thresholds :
    - A score for the “Technology readiness” criterion higher than 2 (as defined in Table 7) means that the technical solution is not available
    - A score for the “Applicable within existing regulations“ criterion higher than 1 (as defined in Table 7) means that regulatory barriers should be investigated

Regulatory priority Index	Technology available?	Regulation needed?	Recommendation
1	YES	YES	Adoption of solution requires regulatory development
2	NO	YES	Adoption of solution requires regulatory and technology developments
3	NO	NO	Technology is not mature
4	YES	NO	Can be applied where problems occur

Table 8 - Regulatory priority index

The performance indicators for each technical solution in the different countries have been aggregated per grid type (LV rural, LV suburban, MV rural and MV suburban grids) in the 4 effectiveness tables reported in [4].

6.2.4 Stakeholder consultation

Before moving on to the analysis of barriers for the ranked list of solutions, a final consultation with the PV industry and other stakeholders involved in the distribution grid electricity sector was organized. These stakeholders were represented by PV and solar industry associations participating to the project, invited external experts and Advisory Committee members.

Based on the outcome of this last consultation round, the ranking of technical solutions was adjusted. The results for the techno-economic indicators were aggregated in three categories (most appropriate, optional, and less appropriate technical solutions) in order to better reflect the position of all stakeholders.

6.3 Evaluation results for LV grids

Table 9 presents the final evaluation results based on the stakeholder consultation. The list of most appropriate solutions (high effectiveness solutions) includes two DSO solutions (the classical network reinforcement and the new product OLTC for MV/LV transformer) and four PROSUMER solutions (storage, reactive power provision by PV inverters and the 2 curtailment variants of PV power). No regulatory barriers have been identified for the DSO solutions (green colour in table). On the contrary, regulatory barriers are present in all countries (red colour in table) towards the use of PV curtailment solutions. The solution *Reactive power provision by PV inverters* can already be applied in Germany, but regulatory barriers are present in Czech Republic, Spain and Italy. The solution *Prosumer storage* can already be applied in Germany and Italy, but regulatory barriers are present in Czech Republic and Spain. Low effectiveness solutions are based on electricity price signals, the sophisticated closed loop operation and solutions less relevant to this voltage level.

Effectiveness of Solutions	Technical solution	CZ	DE	ES	IT
HIGH EFFECTIVENESS	Curtailment of power feed-in at PCC	🟥	🟥	🟥	🟥
	Network Reinforcement	🟩	🟩	🟩	🟩
	Reactive power control by PV inverter Q(U) Q(P)	🟥	🟩	🟥	🟥
	Active power control by PV inverter P(U)	🟥	🟥	🟥	🟥
	Prosumer storage	🟥	🟩	🟥	🟩
	On Load Tap Changer for MV/LV transformer	🟩	🟩	🟩	🟩
NORMAL EFFECTIVENESS	SCADA + direct load control	🟥	🟥	🟥	🟥
	Network Reconfiguration	🟩	🟩	🟩	🟩
	Self-consumption by tariff incentives	🟩	🟩	🟥	🟥
	Wide area voltage control	🟨	🟨	🟩	🟨
	Static VAr Control	🟩	🟩	🟩	🟩
	Booster Transformer	🟩	🟩	🟩	🟩
	SCADA + PV inverter control (Q and P)	🟨	🟥	🟨	🟨
	DSO storage	🟥	🟥	🟥	🟥
LOW EFFECTIVENESS	Demand response by local price signals	🟥	🟥	🟥	🟥
	Advanced voltage control for HV/MV transformer	🟩	🟩	🟩	🟩
	Demand response by market price signals	🟨	🟨	🟨	🟥
	Advanced Closed-Loop Operation	⬜	🟩	🟨	⬜

Table 9 - Effectiveness list of technical solutions for LV grids

Regulatory priority index - Legend
🟥 Adoption of solution requires regulatory development
🟨 Adoption of solution requires regulatory and technology developments
⬜ Technology is not mature
🟩 Can be applied where problems occur

6.4 Evaluation results for MV grids

Table 10 presents the final evaluation results based on the stakeholder consultation. The list of most appropriate solutions (high effectiveness solutions) includes three DSO solutions (the classical network reinforcement, OLTC for HV/MV transformer and network reconfiguration), three PROSUMER solutions (un-supervised reactive power provision by PV inverters and curtailment variants of PV power) and one INTERACTIVE solution (supervised control of PV active and reactive power). No regulatory barriers have been identified for the DSO solutions (green colour in table). On the contrary, regulatory barriers are present for all other solutions in nearly all countries (red colour in table, with exception of un-supervised reactive power provision in Germany). The solutions categorized in low effectiveness are based on electricity price signals, the sophisticated closed loop operation and solutions less relevant to this voltage level.

Effectiveness of solutions	Technical solution	CZ	DE	ES	IT
HIGH EFFECTIVENESS	Network Reinforcement	🟩	🟩	🟩	🟩
	Reactive power control by PV inverter Q(U) Q(P)	🟥	🟩	🟥	🟥
	Curtailment of power feed-in at PCC	🟥	🟥	🟥	🟥
	Active power control by PV inverter P(U)	🟥	🟥	🟥	🟥
	Network Reconfiguration	🟩	🟩	🟩	🟩
	SCADA + PV inverter control (Q and P)	🟥	🟥	🟥	🟥
	Advanced voltage control for HV/MV transformer	🟩	🟩	🟩	🟩
NORMAL EFFECTIVENESS	Static VAr Control	🟩	🟩	🟩	🟩
	SCADA + direct load control	🟨	🟨	🟥	🟥
	Self-consumption by tariff incentives	🟩	🟩	🟨	🟥
	Wide area voltage control	🟨	🟨	🟩	🟨
	DSO storage	🟥	🟥	🟥	🟨
	Prosumer storage	🟥	🟩	🟥	🟩
LOW EFFECTIVENESS	On Load Tap Changer for MV/LV transformer	🟩	🟩	🟩	🟩
	Booster Transformer	🟩	🟩	🟩	🟩
	Demand response by local price signals	🟥	🟥	🟥	🟥
	Demand response by market price signals	🟨	🟨	🟨	🟥
	Advanced Closed-Loop Operation	⬜	🟩	🟨	⬜

Table 10 - Effectiveness list of technical solutions for MV grids

Regulatory priority index - Legend
🟥 Adoption of solution requires regulatory development
🟨 Adoption of solution requires regulatory and technology developments
⬜ Technology is not mature
🟩 Can be applied where problems occur

7 GLOSSARY

Booster Transformer is a transformer of which one winding is intended to be connected in series with a circuit in order to alter its voltage and the other winding is an energizing winding.

Capacity of PV plant is the peak DC power as specified by the module manufacturer for standard test conditions.

Closed-Loop Operation (or Closed Ring Operation) is the method of operation where each point of a given part of a network is fed from two sources along two distinct paths.

Curtailment is a planned reduction of the power production.

Dump load is a device (usually an electric heating element) to which PV generator power flows when the grid cannot accept more feed-in power.

DSO is the abbreviation for distribution system operator

EHV is the abbreviation for extra high voltage (> 230 kV according to IEC)

Fast Voltage Deviations are defined as the variations which occur instantaneously in a network in case a generation plant suddenly disconnects.

Feeder is a power line transferring power between distribution substations and consumers.

Grid hosting capacity is the maximum DER penetration for which the power system operates satisfactorily.

Impedance is the measure of the opposition that a circuit presents to the passage of a current when a voltage is applied.

Meshed grid includes redundant lines, which are in addition to the main lines and organized as backups for the purpose of rerouting power in the event of failure to a main line.

On-Load-Tap-Changer (OLTC) is a device for changing the tapping connections of a winding, suitable for operation while the transformer is energized or on load.

Point of common coupling (PCC) is the point on the public electricity network at which customers are connected.

Priority access to the grid provides an assurance given to connected generators of electricity from renewable energy sources that they will be able to sell and transmit the electricity from renewable energy sources in accordance with connection rules at all times, whenever the source becomes available. In the event that the electricity from renewable energy sources is integrated into the spot market, guaranteed access ensures that all electricity sold and supported obtains access to the grid, allowing the use of a maximum amount of electricity from renewable energy sources from installations connected to the grid.” (Directive 2009/28/EC on the promotion of the use of energy from renewable sources).

R/X is the ratio resistance divided by reactance for a power line.

RES is the abbreviation for renewable energy source

Slow Voltage Deviations are defined as the variations which occur in voltage during normal operation, due to the behaviour of generation and load connected to a given network.

Static VAR Compensator (SVC) is an electrical device which provides fast-acting reactive power in an electrical network under various system conditions.

Supervisory control and data acquisition (SCADA) usually refers to centralized systems which monitor and control entire sites, or complexes of systems spread out over large areas (anything from an industrial plant to a nation).

TSO is the abbreviation for transmission system operator

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