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SERENDIPV

D6.1 Summary of technical constraints and recommendations for PV integration

T6.1 Technical constraints for high contribution of PV to the power network

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Summary

The present deliverable is the final report for the Task 6.1, which provides a baseline for the other tasks in relation to grid integration of PV in the project. Therefore, analyses of the situation in several EU-countries (i.e. Germany, France, Spain, Belgium, Finland and Austria), based on the state of the art, were conducted in this deliverable. The analyses are mainly related to the technical limitations for a high contribution of PV in the power grid, such as grid capacity limitations, high cost of grid reinforcement, need for the communication with PV for better grid integration, need for ancillary services from PV to the grid, need for storages, etc.

This document is initiated by THU as the Task Leader, who focused on the German case, then the inputs were collected from the other partners in the Task considering their countries. The deliverable is produced in the project timeframe from M06 to M18.

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1 EXECUTIVE SUMMARY

1.1 Description of the deliverable content and purpose

This document contains several analyses in relation to the possible **technical constraints** that affects the spread of PV installation. The analyses are mainly based on the state-of-the-art, available national studies and experience of the project partners. The covered constraints in this document are mainly technical barriers for increasing the contribution of PV in the energy system considering the technical challenges, such as grid congestion, grid reinforcement and its high costs, lack of PV data, need for communication with PV for better grid integration, ancillary services from PV for the grid, need for storages etc. The analyses involve six EU-countries which are the countries of the project partners participating in T6.1 (i.e. Austria, Belgium, Finland, France, Germany, Spain). The analyses in this deliverable will be the basis for the future inputs and developments in the other tasks of WP6.

This document has been drafted by THU as the Task Leader, who, in the first step, created a structure of the document and gathered the points to be analysed. The German case was used as the template for the analysis of the other countries, considering the availability of many state-of-the-art studies. Then the inputs were collected from the partners for those countries.

1.2 Reference material

This Deliverable D6.1 has some relevance to the overview information presented in Deliverable D1.1, mainly in relation to the concept of decentralization of the energy generation from PV and its effects on the grid. This D6.1 presents more detailed analysis of these topics as well as the real situation in several EU countries based on the available studies in these countries.

1.3 Relation with other activities in the project

Table 1 depicts the main links of this deliverable to other activities (work packages, tasks, deliverables, etc.) within SERENDI-PV project.

Table 1: Relation between current deliverable and other activities in the project

Project activity	Relation with current deliverable
T6.3, T6.4, T6.5, T6.6, T8.4	The current deliverable feeds these Tasks with the general overview on the situation in several countries in order to improve the orientation of the planned innovations and demonstration in these tasks.

1.4 Abbreviation list

Table 2: Utilized Abbreviations in this Deliverable

Abbreviation	Meaning
ADEME	French Environment and Energy Management Agency
AMQP	Advanced Message Queuing Protocol
AMR	Automatic Meter Reading
APG	Transmission System Operator of Austria
BAS	Basic Scenario without the Addition of Storage Facilities
BESS	Battery energy storage systems
BHKW	Combined Heat and Power Plant
BMWi	The Federal Ministry for Economic Affairs and Climate Action
BMU	Federal Ministry for the Environment, Nature Conservation, Nuclear Safety and Consumer Protection
BSI	German Federal Office for Information Security
CIM	Common Information Model
CLS	Controllable Local System
CoAP	Constrained Application Protocol
CORBA	Common Object Request Broker Architecture
CRE	French Energy Regulatory Commission
CSS	Chirp Spread Spectrum
DDS	Data Distribution Service
DEA	Decentralized Power Plants
DEIE	Operating Information and Exchange System
DER	Distributed Energy Resource
DG	Distributed Generator
DLR	Dynamic Line Rating
DNP	Distributed Network Protocol
DSL	Digital Subscriber Lines
DSO	Distribution System Operator
EDGE	Enhanced Data Rate for GSM Evolution
EEG	The Renewable Energy Sources Act
ElWOG	Federal Act Providing New Rules for the Organisation of the Electricity Sector
EMS	Energy Management System
ESS	Energy Storage System

EV	Electronic Vehicle
FACTS	Flexible AC Transmission Systems
FAN	Field/Farm Area Network
FCR	Frequency Containment Reserve
FEE	The French Wind Energy Association
FIT	Feed-in Tariff
FLM	Overhead Line Monitoring
FRR	Frequency Restoration Reserve
GDEW	Law on Digitalisation of the Energy Transition
GFM	Grid-Forming
GHG	Greenhouse Gas
GIL	Gas Insulated Line
GO	Guarantees of Origin
GPRS	General Packet Radio Service
GPS	Global Positioning System
GSM	Global System for Mobile Communications
GWA	Gateway Administration
HAN	Home Area Network
HGÜ	High Voltage Direct Current Transmission
HIL	Hardware in the Loop
HTTP	Hypertext Transfer Protocol
HVAC	High Voltage Alternating Current
HVDC	High Voltage Direct Current
HYB	Large-Scale Direct Current Connection
ICT	Intelligent feed-in management using information and communication technology
IEA	The International Energy Agency
IEC	International Electrotechnical Commission
IED	Intelligent Electronic Device
IEE	Institute for Energy Economics and Energy System Technology
IEEE	Institute of Electrical and Electronics Engineers
INSEE	French National Institute of Statistics and Economic Studies
IoT	Internet of Things
IP	Internet Protocol
JSON	JavaScript Object Notation

LAN	Local Area Network
LMN	Local Metrological Network
LoRa	Long Range
LPWA	Low Power Wide Area
LV	Low Voltage
LVRT	Low Voltage Ride Trough
MaStRV	Market Master Data Register Ordinance
MITECO	The Ministry for the Ecological Transition and the Demographic Challenge
MQTT	Message Queuing Telemetry Transport
MsbG	German Metering Point Operation Act
MV	Medium Voltage
NABEG	German Grid Expansion Acceleration Act
NEP	Network development plan
ÖMAG	Green Electricity Clearing Settlement Company
OPC	Open Platform Communications
ÖSG	Austrian Health Care Structure Plan
PCI	Projects of Common Interest
PCR	Primary Control Reserve
PI	Proportional Integral
PLC	Power Line Communication
PNIEC	The Spanish National Integrated Energy and Climate Plan
POC	Point of Connection // Point of Common Coupling
POD	Power Oscillation Damping
PPE	Multiannual Energy Programme of France
PPM	Power Park Module
PSTN	Public Switched Telephone Network
PSW	Pumped Storage Power Plants
PtX	Power-to-X
QoS	Quality of Service
RE	Renewable Energy
REE	Electricity Transmission System Operator of Spain
RES	Renewable Energy Source
REST	Representational State Transfer
RoR	Run-of-River

RTE	Electricity Transmission System Operator of France
RTU	Remote Terminal Unit
S3REnR	Regional Grid Connection Schemes for Renewable Energies
SCADA	Supervisory Control and Data Acquisition
SDDR	Ten-Year Network Development Plan
SER	The French Renewable Energy Trade Association
SIL	Software in the Loop
SMGW	Smart-Meter-Gateway
SoC	State of Charge
SO-GL	System Operation Guideline
SoH	State of Health
STATCOM	Static Synchronous Compensator
TAL	Usage of Tal Conductors
TCL	Thermostatically Controlled Load
TCP	Transmission Control Protocol
TSO	Transmission System Operator
UA	Unified Architecture
URL	Uniform Resource Locator
UTM	Universal Transverse Mercator
V2G	Vehicle to Grid
VDE	Association of Electrical, Electronic and Information Technologies
VPN	Virtual Private Network
VPP	Virtual Power Plant
VSC1	Multi-Terminal Operation
VSC2	Point to Point Connection
WAN	Wide Area Network
WBS	Work Breakdown Structure
WLAN	Wireless Local Area Network
XML	Extensible Markup Language

2 INTRODUCTION

The electrical grids, which are mainly built several decades ago, are under the transition from a centralized power supply through some hundreds of large power plants to a decentralized power supply through millions of small Distributed Energy Resources (DER). The control of this high number of distributed unites to meet the demand of the loads and to operate the grid in normal conditions is a real challenge for the grid operators. The majority of these generation units are not as before located in the transmission grid level, which is under the control of the transmission system operators (TSOs), but they are connected the distribution grid level, which is under the control of the distribution system operators (DSOs). A short description of some challenges in relation to grid integration are listed hereinafter:

- **Voltage increase** occurs locally at certain grid nodes, which are usually far from the transformer substations and having high feed-in of DER. This is a main limitation factor for a high DER penetration level, especially for distribution grids. The installation of DER should not lead to voltage violation of a predefined tolerance band at any part of the grid, even in the peak feed-in hours when the reverse power is at the highest value (e.g. the noon for PV generation).
- The installation of DERs in the grid should not lead to **overloading of grid components** such as lines and transformers in order to maintain normal operation. The grid is considered to reach its hosting capacity if at least one component exceeds its nominal capacity defined by the manufacturer, of if the voltage tolerance band is violated.
- The **frequency stability** is an important criterion for a quality operation of the grid, given the control levels (primary, secondary and tertiary) and their timeframe of allowed frequency deviation. Frequency deviation can occur as a result of some unbalance between the energy generation and demand in the grid. This frequency deviation should not lead to a violation of a predefined tolerance band. The frequency stability is usually under the supervision of TSOs. However, TSOs must cooperate more with DSOs in high DER penetration scenarios, since the most DERs are installed at the DSOs grid level.

These concepts, among others, which are presented in this D6.1 were previously introduced shortly with some other details in the Deliverable D1.1, including voltage stability limitation, frequency stability limitation, overloading on grid component, grid hosting capacity of PV, PV data integration and techniques to increase the grid hosting capacity.

Given the grid challenges and considering the lack of information in the distribution grid, especially in the low voltage (LV), there is a need for having good communication and coordination with these generation units. This communication should include the possibility to send the DER control demands and receive measurement to have higher transparency and controllability in the grid. The need for higher transparency is not only because of DER but also because of some new load types, such as electric vehicles, heat pumps and storages. In future scenarios with high DER penetration and more new loads, there is also a need to communicate with the appliances of prosumers (i.e. energy consumers and producers).

A schematic illustration of the introduced ideas is depicted in Figure 1.

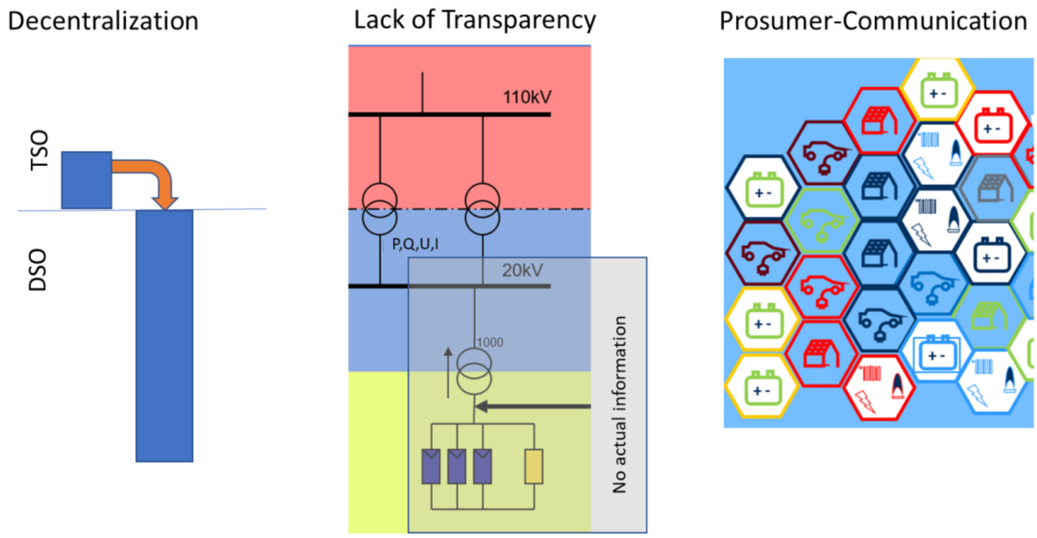

Figure 1: Schematic illustration of some challenges in relation to the energy transition in the grid

3 TECHNICAL LIMITATIONS FOR THE FURTHER INCREASE OF PV PENETRATION (EFFECTS OF DECENTRALIZATION)

This chapter summarizes the grid technical limitations and constraints for the further increase of PV penetration in the grid based on analysis of the constraints found in different studies from several EU-countries, which the participating partners of this Task belong to. In addition, a summary of the grid hosting capacity of PV as well as the required grid expansion costs, based on state of the art, is presented.

3.1 Analysis of the grid impact of PV in different countries

With the high expansion of PV power generation, the grid will change from a purely distributing grid to a grid with a feed-in case. This is associated with new and so far, little considered problems. Probably the most significant problem in this case is the possible **violation of the voltage band** that occurs when PV power production exceeds consumption in a specific section of the grid. However, it must be said that this is by far not the only new problem. For this reason, the legal institutions and grid utilities tried to adapt such problems by proving guidelines and norms such as the German one of VDE-AR-N 4105. According to VDE 4105, the low-voltage grid should be also considered as a grid with generating plants due to the spread of PV plants and the associated reverse power flows. The norm requires that the voltage change generated by a single generating plant must not exceed 3% at the point of common coupling (POC). Phenomena such as flicker, harmonics, voltage asymmetries, etc. are to be avoided as far as possible. Furthermore, possible **overloading for some lines and transformers** must be checked. Moreover, precautions must be taken against **frequency increase and frequency drop**. These regulations are necessary because a generator increases the frequency when feeding into the power grid and thus the PV must be disconnected if the frequency increase exceeds an upper limit. Furthermore, the short-circuit currents within low voltage (LV) and medium voltage (MV) grids increase because of the presence of distributed generators. Moreover, it should be taken into consideration that different level of power flows as well as their direction (reverse power flows between different voltage levels) have an impact on protection device settings.

3.1.1 Germany

Table 3: Summary of some grid studies in relation to grid impact of PV in Germany

Studies	Investigations related to the topic	Main findings
BMWi study [1]	This study analyses the expansion of renewable energy with three different scenarios: - Scenario EEG (renewable energy law) 2014: installed green energy of 128 GW by 2032 (60 GW wind, 59 GW PV and 9 GW other) - Scenario "Network development plan" (NEP): installed Green Energy of 139 GW by 2032 (65 GW	Distribution of PV plants in the different grid levels: - 10 % High-voltage grid - 30 % Medium-voltage grid - 60 % Low voltage grid Problems arising from the expansion of PV systems: - Need for reactive power management, mainly in rural areas. - Need to expand the existing cable infrastructure in the low-voltage grid in order to avoid violations of the voltage band - Need to expand the existing cable infrastructure in the medium-voltage grid in order to avoid

	Wind, 65 GW PV and 10 other) - Scenario "Federal States": installed green energy of 206 GW by 2032 (111 GW wind, 85 GW of PV and 10 GW other)	violations of the voltage band but both wind and PV energy lead to this problem - Additional transformers need to be installed due to reverse power flow into higher voltage levels.
Dena [2]	One of the goals of the Dena grid study was to generate time series of electrical feed-in from wind and PV energy. The data for the photovoltaic simulation comes from the BNU lead scenario, which aims to reduce CO2 emissions to 20% by 2050 compared to 1990 and to achieve a 50% share of green electricity in German electricity production.	The expected PV expansion in this study goes from 1 GW in 2005 to a projected 20 GW in 2020, which is more than double the PV expansion projected in the previous Dena study. This new expectation results from the increase in installed PV capacity by 8,690 MW in the period from 01/2009 to 08/2010, bringing the installed PV capacity to 14.7 GW. The actual installed PV capacity by November 2020 is 53.6 GW and far exceeds the forecasts of this study. At the time of writing, the impact of PV on reactive power is still comparatively small, but already noticeable. This study proposes coils in the order of 20,000 MVAr, mainly to compensate the reactive power relating with wind power plants connection. According to the Dena 1 distribution grid study, the need for grid expansion can be reduced through the curtailment of decentralized energy plants, as the grids are designed for power peaks. The curtailment of these production plants is set at 70%, which results in a reduction of the annual feed-in of approx. 2%. The regulation of decentralized energy plants enables not only the avoidance but also a time delay of grid expansion measures. Intelligent feed-in management using information and communication technology (ICT) could reduce energy loss, as it is only necessary to regulate power in critical grid situations.
Hesse [3]	Analyses of the current and future influence of PV and wind systems on the Hessian electricity grid. At the time of writing this study, Hesse has a share of installed green power capacity in its energy generation of about 14%. The state aims to increase the share of renewable energy by, firstly, expanding the installed PV capacity: - 1.77 GWp by 2014 - 3.00 GWp by 2024	Type of PV power generating plants in Hesse: - 80% rooftop systems - 20% ground mounted systems This study assumes that the distribution of rooftop and ground mounted PV plants will not change in the coming years. Problems arising from expanded PV power production: - Reverse power flow between the different voltage levels and the transmission grid - Additional feed-in and consumer power in the low-voltage grids will increasingly lead to current- or voltage-related or even combined limit violations.

	- 4.65 GWp by 2035	
Baden-Württemberg [4]	This study explores the problems that come with high share of PV (and to some degree wind) and also its localization. It also looks at the impact which expanded battery usage in PV installations will have. Distribution of feed-in of generated PV energy by grid level: - 0% into the high-voltage grid - 25% into the medium-voltage grid - 75% into the low-voltage grid	For the planning of the power grid, the design is increasingly moving from the high-load case to the feed-in case. Since the development of decentralized feed-in has a strong regional character, the grid impact of PV is more essential in certain regions. For example, in certain (semi-)urban regions, the forecast of expansion of decentralized energy plants is low, so that here the load case will probably continue to be more relevant for the grid planning. The impact of PV systems on the grid infrastructure is somewhat mitigated by the expected increasing combination of PV systems with a battery system: - 13,4% by 2015 of PV will combined with a battery - 20,0% by 2020 of PV will combined with a battery - 25,0% by 2030 of PV will combined with a battery
Bayern [5]	Analysis of the installed PV power in Bavaria and its impact on more rural areas as well as the impact on different energy networks, in this case the gas network.	As of the time this document was written, Bavaria had an installed green electricity capacity of around 13 GW, of which 10.18 GW were PV. Furthermore, about 30 % of all installed PV systems in Germany are located in Bavaria. Already at the time of this study, PV feed-in often exceeds the demand for electricity in rural areas. This electricity must then be transported from the low-voltage grid to the higher grid levels, for which the historically developed grids are not designed. The variability of PV power and other green power generators and the lack of storage capacities force the Bavarian grid expansion to install more gas turbines to ensure security of supply, which indirectly leads to an expansion of the gas grid.

The possible grid bottlenecks with PV are mainly to occur in the low-voltage grid with small to medium-sized systems and maybe in the medium-voltage grid for larger PV systems. Furthermore, these problems are concentrated in more rural areas and more in the south of Germany. The most important problem arises in the form of daily fluctuations in the feed-in, when the feed-in by PV systems exceeds the consumption and thus voltage violations occur as a result of the additional power feed-in in the grid. In addition, reactive power management is becoming increasingly important.

3.1.2 France

Table 4: Summary of some grid studies in relation to grid impact of PV in France

Studies	Investigations related to the topic	Main findings
RTE & IEA [6]	Analysis of a grid system with high renewable energy penetration.	Beyond certain thresholds (60% to 80% of grid-following wind and solar PV instantaneous penetration – over total generation), system stability can be at risk because of this lack of grid-forming capability. In scenarios with very high shares of variable renewables such as the ones studied in this report, by contrast, the stability would need to be ensured by the power electronics of wind and PV generators, which is currently not possible. "Today's […] PV generators are operated as "grid following" units. They only "read" the frequency set by the alternating current signal in the AC power system, they do not impose a voltage and frequency reference to the network as do conventional generators. As the power system's share of variable renewables increases, the robustness of the frequency signal is bound to decrease if variable renewables continue to operate in 'grid following mode', jeopardising system stability."
RTE (Futurs énergétiques 2050 Principaux résultats) [7]	Analysis of the future French energy share.	Any new production plant implies a connection and possibly an adaptation of the network. In the energy transition equation, the grid plays a major role. These networks will have to accelerate their transformation to make the energy transition possible. In the coming years, the number of grid connections will raise, and the asset connection to grid frequency will be a challenge on both technical and organizational side. The partners of the new PV production will be the industry, the inhabitants, the producers, and the associations. This transformation takes place in societal context where results must come quickly. Moreover, the opposition to renewable project, including PV, is systematic. Network connection forecasts are uncertain at the local scale and require agility from the DSO.
PPE [8]	State guidelines regarding the French energy share targets. Assessment of the actual energy share and impact of transformations on it.	The electrical grid is evolving from an historical decentralized production, made with high power facilities directly connected to the transmission network (managed by the French TSO) to a dispatchable production, near to the consumer and connected to the distribution network (managed by the DSO).

		More of 90% of the electricity production is injected on the transmission network. That includes hydroelectricity and nuclear power. The number of wind farms connected to the distribution network is limited and with the growing power of the farms that is not up to change. The new PV plants are connected to the distribution network. At the end of Q3 2019, 433k PV production sites for a total of 27.5GWp installed power. At the end the PV will have most of his impact on the distribution network assuming the French state guidelines.

Several scenarios are based on a massive penetration of renewable electricity production up to 2050.

The characteristics of PV plants came with constraints for the grid. From the geographical dispatchability of assets to the variability of production.

The actual grid was designed to produce a large amount of energy at one point and transport it by decreasing the power at each step to cover the consumer needs. New technologies require a different approach by increasing the power to transport the production. These challenges are conditioned by the balance between production and consumption: frequency. Different possibilities are explored between the development of current methods to ensure stability and more local management for PV production.

3.1.3 Spain

Table 5: Summary of some grid studies in relation to grid impact of PV in Spain

Studies	Investigations related to the topic	Main findings
Integrated National Plan for Energy and Clime (PNIEC 2021-2030) [9]	Analysis of the future Spanish energy share (2021-2030)	The MITECO ministry establishes two possible scenarios for the future development of renewable technologies in Spain: a) Trend Scenario (without additional measures); b) Target Scenario (with additional measures). In the Trend Scenario, greenhouse gas (GHG) emissions in Spain increase by 5.6% in 2030 compared to 1990, while in the Target Scenario, GHG emissions are reduced by 23%. In the Trend Scenario, the total installed capacity in Spain increases from 114.5 GW in 2020 to 126 GW in 2030. The main increases come from wind and solar photovoltaic technologies, with around 10 GW each. In the Target Scenario, the total installed capacity increases to 161 GW in 2030, with the main increase coming from solar photovoltaic technology, with approximately 30 GW.

		The current installed PV capacity, April 2022, is 15.9 GW. The most ambitious scenario considers 39 GW of installed PV capacity as the target by 2030. This 39 GW would mean about the 24% of the total installed capacity in Spain [Table A.19 of [9]]. With that aim, the transmission network development plan [10], considers the integration of additional 19 GW of PV capacity. Regarding the generation, the renewable generation in the target scenario by 2030 is expected to be 74% of the total generation, being about the 20% coming from PV installations [Table A.22 of [9]].
Electric Transmission Network Development Plan 2021-2026 [10]	Identified effects on the grid due to the expected increase of renewables	The design and planning of the network will play an essential role in the integration of a greater amount of intermittent electricity generation, based on the connection of more generation, given that the renewable resources (geographically concentrated) and the consumption centres are not closely located. Current identified needs are linked to the re-dispatch of generation units in certain areas representing additional costs for the system due to technical congestions. Mainly, such needs focus on the requirement of additional resources for voltage control, although others, for example related to the curtailments of renewable generation in some areas, are already being detected. Moreover, in the horizon 2026 more additional necessities are expected to appear due to overloads in the transmission and integration of the new renewable generation.
	Renewable generation – Curtailment level	With no extra investments in the current electricity network, by 2026, there would be curtailments of about 15% of renewable production with respect to its potential production and the integration of the renewable generation would be 62%. With the expected investments in [10] in the transmission network, the curtailed energy could be reduced to 4% and the renewable generation would reach the 68%.
Self-consumption Roadmap [11]	Rooftop self-consumption Roadmap	Based on the potential analyses carried out, this Roadmap sets a target to reach 9 GW of installed capacity in 2030 with the implementation of the measures described in this Roadmap. This target could increase to 14 GW of installed self-consumption in 2030 in the event of a very favourable scenario of high penetration, which would be achieved thanks to the multiplier effect of the measures adopted and, in particular, of the additional mobilization of all stakeholders, from civil society to the energy sector, in order to achieve a high penetration rate.

Integrated National Plan for Energy and Clime (PNIEC 2021-2030) [9]	Participation of renewable generation in the ancillary services for the system	Although the renewable installations are allowed to participate in the ancillary services markets according to Royal Decree 413/2014 [12], currently such participation is very low (apart from hydraulic technology). For that reason, one of the identified measures for the integration on the electricity market within [9] is the progress in the participation of renewable energies in ancillary and balancing services. For example, the wind technology is increasing its participation in the balancing services and is working on the participation in other services such as voltage control and inertia emulation [13].
Operating procedures – Spanish System Operator [14]	Participation of renewable generation in the ancillary services for the system	The Operating Procedures (managed by the Spanish System Operator, REE) are constantly evolving in order to ease the participation in the ancillary services markets, and also to include the participation of demand and storage facilities in such markets (e. g. reduction of size requirements). For example, by April 2023, the Spanish aFRR service will be deeply modified as a first step in order to be connected to the aFRR European platform (PICASSO) by April 2024. At that time, one of the main modifications will be the submission of energy bids instead of the current capacity bids. In addition, no upward/downward ratio will be mandatory for the submitted bids. All these updates in the operating procedures will ease the participation of the PV installations in the ancillary services markets, although the competence will also increase.
Information system of the distribution system operators. Design specifications [15]	Common platform at distribution level for the information exchange in real time	An Information System for Distribution Network Operators (SIORD) is currently under development. Its main objective is, through a common platform for the information exchange in real time, to unify and, thus, simplify and minimise the cost of exchanging information and instructions between generation and demand control centres and distribution network managers. With SIORD, these control centres of generation and demand facilities can communicate through a common channel with all distribution network managers, without the need of multiple communication channels with each distribution system operator. This platform would be a common, simple and standard solution for all distribution network managers in the national territory.
Circular 1/2021 of the National Commission on Markets and Competition (CNMC) [16]	Available connection capacity	Since January 2021, the distribution and transmission system operators must keep accessible on their website detailed information on the available capacities at the nodes of their networks with voltages greater than 1 kV. This information is monthly updated.

3.1.4 Austria

Table 6: Summary of some grid studies in relation to grid impact of PV in Austria

Studies	Investigations related to the topic	Main findings
Innovative Energy Technologies in Austria Market development 2020 [17]	Documentation and analysis of the market development of technologies for the use of renewable energy	The contribution of photovoltaics to domestic electricity generation has increased rapidly over the period (2005 – 2019) under review and now amounts to already 2.4 %. In 2020, a significant increase in newly installed PV systems of 340 MWp was achieved. In total, Austria has an installed capacity of about 2000 MWp.
Association of Austrian Electricity Companies (2020) [17]	Grid calculations and influence of the developments of electromobility and photovoltaics on the Austrian electricity grid divided in 3 scenarios: EV10, EV30 and PV2030	The Austrian government envisages a power supply from 100% renewable energies by the year 2030. This requires an additional generation of 27 TWh for the period 2020 - 2030, which is to be ensured by means of an expansion of hydropower (5 TWh), wind power (10 TWh), biomass (1 TWh) and PV plants (11 TWh). Compared to other renewable generation technologies, most of the additional installed generation capacity required is expected to come from the expansion of PV capacity (+11 GW).
Flexibility Sources and Demand in the Electricity Austria's Electricity System 2020/2030 [18]	This study shows the need for flexibility up to 2030. It also shows that it is therefore necessary to further develop the technical potentials considered and to make them available both for the markets as well as to make them available for the distribution grid.	In the analysis of the flexibility potential of the generators, a distinction is made between thermal power plants (natural gas, biogas, biomass, waste incineration) and volatile renewable generators (natural gas, biogas, biomass, waste incineration) and volatile renewable generators (run-of-river plant, photovoltaics and wind power. Due to the planned shift towards more renewable energies, the highest (negative) potentials are seen in photovoltaics (about -7500 MW) and wind power (about -6500 MW). This study identifies the increasing penetration of distributed generators and new consumers in the distribution grid, and the associated increasing operation of these grids at their technical limits, as the greatest challenge facing distribution grid applications.

morePV2grid - More functionalities for increased integration of PV into grid [19]	This report shows local control concepts for active grid support by PV inverters based on field tests.	In this study a feeder of a local transformer station with 43 prosumers and an installed PV power of in total 16 kW_p was selected to investigate 7 concepts for voltage regulation. The effectiveness of the reactive power control is very much dependent on the R/X ratio. Its compensation of the voltage rises between 20 % and 80 % can be achieved. With the use of the voltage-dependent active power control P(U), an increase in voltage caused by the voltage increase caused by generation plants can be limited. The dynamic investigations of the voltage-dependent reactive power control Q(U), the voltage-dependent active power control P(U) and the combination P&Q(U) have shown in simulation, laboratory and field tests that with reasonable parameters there is no oscillation tendency is present.

The increasing PV production between 2005 and 2019 has led to a significant annual number of new PV-systems installed, which achieved in 2020 an amount of 340 MWp. For the period 2020 – 2030 an additional PV capacity of 11 GWp is required to reach Austrian's governments goal of a 100 % power supply from renewable energies. Due to this shift towards more flexible renewable energy production a high negative potential is seen in photovoltaics. Hence, studies identify the increasing renewable energy production as a great challenge facing distribution grid applications. To address these problems, research projects investigate voltage-dependent power control of PV inverters into the local grid.

3.1.5 Belgium

Table 7: Summary of some grid studies in relation to grid impact of PV in Belgium

Studies	Investigations related to the topic	Main findings
Belgian TSO Elia "Adequacy- en flexibiliteitsstudie voor België 2022 – 2032" [20]	Periodic study on adequacy and flexibility needs in Belgium for the time horizon 2022-2032:	Belgian TSO Elia looked at the adequacy of the overall Belgian electricity system to meet demand at all points in time. Being a TSO, the focus is on security of supply, system balancing, and flexibility needs. Nuclear constitutes of 40 to 50% of the Belgian energy mix. However, in accordance with national regulations nuclear should be entirely phased out by 2025. Furthermore, this densely populated region has limited possibilities to increase their share of renewables in comparison to other European countries. Nevertheless, a record installation rate of 1 GW solar power was achieved in 2020 cumulating to a total installed capacity of 6 GW in Belgium (Solar Power Europe 2021 [21]). Based on estimations of different scenarios the total installed PV capacity in 2030 ranges between 6.2 and

		12.1 GW (Meinke-Hubeny et al. 2017) [22]. Worth noticing is that the lower range is at the time of writing almost achieve, as mentioned before. Another study suggests a span between 8.5 and 13.4 GW for the same year (Elia Group 2021). The nuclear phase out, in combination with increased amount if intermittent energy sources, such as PVs, leads to increased need for flexibility. Even though the grid capacities are seemingly good in Belgium, the need for flexibility will substantially increase in the future. According to simulations, the needed flexibility amounts to 5480 MW upward and 4720 MW downward flexibility. Within a reaction span of 15 minutes the provided flexibility should be 2530 MW upwards and 2020 MW downwards while 440 MW (up) and 460 MW (down) has to be ramped up within 5 minutes.

3.1.6 Finland

Table 8: Summary of some grid studies in relation to grid impact of PV in Finland

Studies	Investigations related to the topic	Main findings
The Finnish Innovation Fund Sitra (2021) [23]	The study investigates two scenarios of decarbonisation in Finland by 2050: • Direct Electrification Scenario – widespread electrification • Increased PtX Scenario – broader electrification indirectly via e-hydrogen and other synthetic fuels	• Installed solar PV capacities are expected to reach 2 GW by 2050 • Battery energy storage systems (BESS) can provide fast response to replace the decreasing traditional kinetic inertia of the power system • Behind-the-meter solar PV can decrease annual energy demand and decrease peak power • BESS and inverter-based generation (PV) could support voltage control
Child et al. (2020) [24]	The study investigates the role of PV prosumers in the transition to a 100% RE system in Finland	• Installed solar PV capacity reaches 60 GW by 2050 • Greater transfer of power occurs during dark cold winter months from distant wind turbines • More local generation in summer months during long days • Electricity tends to move from north-to-east and west-to-east reflecting the high wind resource areas, while PV is more localised need the demand centres

Finland aims to become carbon-neutral by 2035, primarily relying on wind, solar, biomass and nuclear power plants and carbon sinks such as land use, land use change and forestry (LULUCF). According to energy transition studies, Finland is expected to be primarily powered by wind power by the end of the transition, with solar PV following second. Subsequently, the grid reinforcements are primarily related to taking advantage of wind resources in the north of the country. Meanwhile, the majority of the population lives in the south of the country where solar energy is most prevalent.

3.2 Grid hosting capacity and need for grid reinforcement in several countries

It is difficult to find accurate numbers about the capacity of the existing grids, as the general consensus is that the electricity grid urgently needs to be upgraded to keep it secure in the future. There are new demands that have not been taken into account in the design of the grid, mainly in the case of reverse power flow. In this case, the grid was originally designed for centralised production, but with the virtual disappearance of nuclear power and the foreseeable phase-out of coal-fired power production, the expansion of renewables will be inevitable. The distribution of renewable energies creates a decentralised system from a previously purely centralised power grid. In this section, some general information about this topic will be collected from existing studies for several EU-countries.

3.2.1 Germany

Studies	Investigations related to the topic	Main findings
Dena [2]	Analyses of the state of the art and the future problems with real and apparent power	The permissible voltage range at the nodes of the 380 kV grid is 380 kV to 420 kV. Feeding 500 MVAr from one side of the 380 kV circuit requires a reactive current of approx. 760 A. The amount of active current that can be transmitted at the same time results in 2700 A of the circuit. This means that about 4% of the thermally permissible transmission capacity is occupied by the reactive current transport. A problem limiting the Grid Hosting Capacity is the non-transferable power between individual grid regions. There are many interconnections that are suitable for the planned expansion, but also many where the grid needs further capacity, which can range from 100 MW to 9600 MW depending on the scenario. Another problem is that the capacity of the power grid can fluctuate by up to 20% depending on the weather conditions. This is due to the fact that the maximum temperature of the power line is reached faster on a warm, sunny day than on a cold, rainy day.
BMWI [1]	Investigates where renewable energy producers bring their	Share of the various electricity grids with expansion requirements in the total electricity grid: - 8% of low power grids

	energy into the power grid. The German electricity grid currently integrates around 61 GW of wind and solar energy, most of which is fed into the low-voltage grid.	- 39% of medium power grids Distribution of affected parties Network operators: - 35% of low-voltage network operators - 64% of the medium-voltage grid operators At the time of writing, only a few rural grid operators (5% of all grid operators) have an installed capacity for renewable energy systems per extraction point that is higher than the respective annual maximum load. Depending on the voltage level and the underlying scenario, between 58% and 76% of the necessary grid expansion measures will have to be implemented by 2022 to guarantee an n-1 secure electricity grid. The grid expansion requirements up to 2032 broken down according to its scenario: - To achieve the expansion targets of the "EEG 2014" scenario, a total of 131,000 km of cables must be laid and 48,000 MVA of transformer capacity installed by 2032. - To achieve the expansion targets of the "NEP" scenario, a total of 165,885 km of cable must be laid and 62,396 MVA of transformer capacity installed by 2032. - To achieve the expansion targets of the "Federal States" scenario, a total of 279,315 km of cable must be laid and 129,226 MVA of transformer capacity installed by 2032. The necessary expansion requirements in German distribution grids for the integration of renewable energies in the case of a purely conventional grid expansion are shown in the "EEG 2014" scenario up to the year 2032 and can be broken down by voltage level as follows: - Low-voltage grid: 50,393 km of new lines and new transformers with a capacity of 14,978 MVA - Medium-voltage grid: 70,104 km of new lines and new transformers with a capacity of 32,941 MVA - High-voltage network: 10,820 km of new lines
Hesse [3]	Analysis of the probability of limit violations for the low voltage grid	The study shows the distribution of the probabilities of limit violations in the low-voltage grids over the calculated amount of energy scenario properties. Probability of a Limit violation by 2024: - 50% of the Grids do not expect any limit violations - 40% of the Grids are at risk of a limit violation - 10% of the Grids are at a high risk of a limit

		by 2034: - 25% of the Grids do not expect any limit violations - 43% of the Grids are at risk of a limit violation - 32% of the Grids are at a high risk of a limit violation Another way to look at limit violation is to look at the type of limit violation, namely voltage violation, line overload and transformer overload. Percentage of limit violations per category in relation to the total number of violations for the years 2024 and 2034. 2024: - Voltage violation: 50% - Line overload: 6% - Transformer overload: 24% 2034: - Voltage violation: 18 % - Line overload: 5% - Transformer overload: 35% There is a clear shift from most voltage violations in 2024 to more transformer overloads in 2034. Moreover, these problems are not mutually exclusive. For example, the probability of a simultaneous voltage violation and transformer overload increases from 16% in 2024 to 31% in 2034.
Baden-Württemberg [4]	This Study goes into detail on how the planning process has changed with renewable green energy production, especially with the reverse power case	The market-oriented operation of flexibility options can lead to a strong increase in peak load in the distribution grids. The peak load can be slightly reduced by grid-supporting operation of flexibility options (reduction to 85 % medium power grid and 77 % low power grid). Complete compensation of wind and PV feed-in through these flexible options are not possible. In all three voltage levels, the feed-in case proves to cause higher load and is thus much more relevant for planning of the grid expansion. The reason for this is that the installed power from decentralized energy systems significantly exceeds the peak load for which the grids are designed, which assumed the load to be constant over the entire lifetime. Operating cases for the estimation of grid hosting capacity for medium voltage: - Heavy load case: 100% load, 0% DEA - Reverse flow case: 30% load, 85-100% DEA Operating cases Low voltage:

		- Heavy load case: 100% load, 0% DEA - Reverse flow case: 20% load, 85-100% DEA
Bavaria [5]	Problems facing the Bavarian grid capacity with its thermal limit for transferable power at the 380 kV level and the importance of the European super grid for network stability	As of 2010 the Bavarian electrical energy demand was at about 80 TWh with about 75% of it used for industrial purposes. The biggest problems with the Bavarian grid are: - the increasing fluctuation of feed-in by green power producers. In 2012, the maximum fluctuation on any one day was 3.5 GW for wind and 5.4 GW for PV - the increasing decentralization of energy producers - due to the nuclear phase-out, Bavaria loses about 46% of its base-load capable power generation capacity. To counteract these problems, Bavaria's integration into the European super grid is extremely important to ensure stability at around 50 Hz. Due to the partial shutdown of nuclear power plants and the expansion of renewable energies, the volume of active power adjustments in Germany almost doubled from 2.0 TWh in 2010 to 3.9 TWh in 2011. The thermally transferable power per circuit at the 380 kV level is between 1,790 MVA and 2,738 MVA for overhead lines and about 1,120 MVA for underground lines. This becomes problematic mainly due to the very long distances between the power producer (northern Germany) and the consumer (Bavaria)

As it turns out, the grid needs to be expanded a lot, especially in rural areas, while there is less need for expansion in urban areas. Furthermore, the exact expansion required is difficult to determine, as renewable energies experience a strong daily fluctuation. In general, it can be said that all levels of the electricity grid and a large proportion of the grid operators are affected by the need for expansion. The situation is aggravated by the fact that renewable energies are currently poorly suited for base load supply due to a lack of storage capacities and strong daily fluctuations, but this role is becoming increasingly important due to the discontinuation of nuclear and, in the foreseeable future, coal-fired electricity.

3.2.2 France

Studies	Investigations related to the topic	Main findings
RTE (Schéma décennal de développement du réseau) [25]	Grid schemes by 2030	The capacity of onshore RE to be connected per year has been stable since the beginning of the 2010s, around 2 GW per year, largely for onshore wind and solar. This rate is set to increase significantly: the trajectory of the PPE (Plan pluriannuel de l'énergie,

		multiyear energy plan) requires reaching nearly 6 GW/year for these two energies, and around 1 GW/year for offshore wind. The volume of projects under development has tended to increase in recent months, which represents an important challenge for their integration on the grid. Since 2011, this integration is planned by grid connection schemes called S3REnR (schémas régionaux de raccordement au réseau des énergies renouvelables). The S3REnR are approved by the institution representative of the localization. Together, the 21 schemes allow 27.6 GW hosting capacity in France. The capacity affected by French localization and the percentage already affected (May 2019): • "Haut de France": 3091 MW; 70% • "Ile de France": 975 MW; 16% • "Haute Normandie": 923MW; 24% • "Basse Normandie": 733MW; 13% • "Champagne Ardennes": 1284MW; 88% • "Lorraine": 890MW; 71% • "Alsace": 471MW; 21% • "Bretagne": 1065MW; 35% • "Pays de la Loire": 1278MW; 50% • "Centre": 1683MW; 35% • "Bourgogne": 1479MW; 49% • "Franche-Comté": 731MW; 42% • "Poitou-Charente": 1513MW; 78% • "Auvergne": 586MW; 50% • "Limousin": 591MW; 54% • "Rhone-Alpes": 2569MW; 19% • "Aquitaine": 830MW; 100% • "Midi-Pyrénées": 1705MW; 38% • "Languedoc-Roussillon": 1729MW; 42% • "PACA": 1549MW; 63%
PPE [8]	State guidelines regarding the French energy share targets. Assessment of the actual energy share and impact of transformations on it.	In the ten-year network development plan (SDDR) [25], the TSO anticipates a need for the creation and reinforcement of structures of around 560 km per year between 2021 and 2035, including approximately 350 km of structural adaptations to the networks, most of which will be done on the distribution network. This concerns the renewal of the old network, the interconnections, and the connection of renewables. The network can accommodate without major reinforcement up to a total of 50 GW of installed

		renewable wind and solar power capacity, with flexibility solutions in counterpart. The 50 GW threshold should be reached from 2025 onwards. Beyond that, more structural reinforcements will be necessary via the reinforcement of certain historical north south axes in particular. The network should be able to accommodate between 10 to 15 GW of offshore renewable generation capacity by 2035. By 2035, RTE also plans to double the interconnection capacity for some 15 GW of commercial capacity (including 8 GW by 2025).

The French environmental objectives foresee covering a part of the growing electricity consumption by the development of renewable energies. The grid is being pushed to its limits, especially in terms of distribution, with the strong decentralization of these new productions with power fluctuations imposed on the grid.

Some regions of the country have already reached their maximum capacity. A development plan has been launched by the government to cover the expected penetration of renewable energies: S3Enr. Interconnection capacity is an equally important issue for the development of the grid. The transmission system operator intends to double its capacity.

3.2.3 Spain

Studies	Investigations related to the topic	Main findings
REE (Red Eléctrica de España) – Spanish System Operator [26]	Spanish Electricity System Report 2020	During 2020, Spain has maintained its commitment to the efficient development of the transmission grid, through the commissioning of facilities that contribute to the energy transition, aimed at integrating as much renewable generation as possible, promoting electrification and improving interconnections between systems, guaranteeing the security of supply and ensuring the quality of service. In 2020, the planned pace of commissioning continued: • 116 kilometres of circuit and 93 substation positions added. • The total length of circuits in the national grid raised to 44,553 kilometres and 6,176 positions at the end of the year. • The transformation capacity increased by 1,430 MVA, bringing the total installed national transformation capacity to 93,895 MVA. • The last interconnection put into service between Spain and France (Baixas-Santa Llogaia) doubled the electricity exchange capacity between Spain and France (from 1,400 MW to 2,800 MW). However, despite this expansion, the degree of interconnection

		of our country is still far below the objectives set by the European Union of 10 % and 15 %, for 2020 and 2030 respectively. • The Spanish National Integrated Energy and Climate Plan (PNIEC) made this clear and proposed to increase the exchange capacity with Portugal up to 3,000 MW and with France up to 8,000 MW.
Electric Transmission Network Development Plan 2021-2026 [10]	The development plan encourages the use and improvement of the existing network, minimizing the environmental impact of the plan	The connection of the new wind and photovoltaic renewable generation (about 19 new GW of photovoltaic) tries to be as efficient as possible, taking advantage, whenever possible, of positions and substations already existing or planned. Only 13% of the necessary connections require the development of new substations, while 12% require new extensions in substations. The remaining connections are deployed in positions of the starting network, having granted access and being actions contemplated in planning 2015-2020 or planned under the Royal Decree Law 15/2018. 21% are considered connected to the distribution network through the existing transmission-distribution interface or through planned new reinforcements.
Integrated National Plan for Energy and Clime (PNIEC 2021-2030) [9]	An adequate degree of electrical interconnection Lower curtailments of renewable energy (income losses for producers for the energy generated that is not consumed, nor can be exported)	The interconnections will ease the integration of renewable generation facilitating the export to other systems. Currently, the interconnection ratio in Spain, below 6%, is still far from the recommended target at European level (15% of interconnection capacity over the total installed capacity). The new interconnections scheduled for the period 2021-2030 will increase the exchange capacity up to: • 3,000 MW with Portugal • 8,000 MW with France

3.2.4 Austria

Studies	Investigations related to the topic	Main findings
Grid development plan 2021 [28]	Development plan of the Austrian's transmission grid according to § 37 ElWOG 2010	The grid reserve has become an essential prerequisite for stable and secure grid and system operation ensuring the security of Austrian´s supply. The conversion of the electricity system to 100% renewable energies, as well as the measures necessary for this (especially grid expansion) are not coordinated.

		The associated costs have risen massively in recent years (2014 still €4 million; in 2017 already €92 million and 2020: €132 million). These costs are part of APG's grid costs and have to be borne by the grid customers via the grid tariffs.
Cost/benefit analysis of transmission grid expansion [29]	This study shows that the need for flexibility up to 2030. It also shows that it is therefore necessary to further develop the technical potentials considered and to make them available both for the markets as well as to make them available for the distribution grid.	The main focus is put on the following specific measures and technology developments: • Completion of two major 380 kV high-voltage AC overhead line projects to close the so-called “380 kV HVAC transmission ring” in Austria. • Increasing/upgrading PHS capacities to support balancing of electricity systems in neighbouring countries. • Studying the impact of further increase of wind (eastern part of the country) and notably PV (across the country) penetration. • Studying the growing load flows from north to south, also including the possibility of a future east-west HVDC link from Austria to Slovakia. • Implementing Flexible AC Transmission Systems (FACTS) and Dynamic Line Rating (DLR) based overhead lines. • Furthermore, the impact of high/low Run-of-River (RoR) electricity generation on the transmission grid is studied for the time horizon 2050.

The significant increase in installed PV systems and in general the expansion of renewable energy production (+ 27 TWh) by the year 2030 pushes distribution and transport grids to their limits. Hence, the grid reinforcement, an optimization of the existing grid and the flexibility management are future challenges for a stable and secure grid and system operation. The main grid reinforcement projects for transmission lines are derived from the grid development plan and envisage, above all, the closure of the 380 kV ring with the Salzburg line and in the south of Austria as well as efficient east-west transport lines and in the west of Austria.

3.2.5 Belgium

Studies	Investigations related to the topic	Main findings
Belgian TSO Elia “Adequacy- en flexibiliteitsstudie voor België 2022 – 2032” [20]	Periodic study on adequacy and flexibility needs in Belgium for the time horizon 2022-2032	Belgium interconnection capacity with its neighbouring countries is the highest in central western Europe of all countries with commercial demand side response. When comparing the ratio of import capabilities to the average peak demand, Belgium ranks number one summing up to 60%. Moreover, Belgium has the highest ratio of commercial demand side response and battery capacity seen to its peak demand in the same region. The estimated rate for 2015 is 16%. The large interconnection capacity

		and demand response availability allow Belgium to deal with intermittent renewables quite well.
Flemish DSO Fluvius "Investeringsplan Elektriciteit voor de DNB's bij de werkmaatschappij Fluvius" [30]	Electricity investment plan for the DSOs at Fluvius	Fluvius is the DSO for the Flemish region, managing the low voltage and parts of the medium voltage grid. Currently, the greatest burden on the low-voltage grid is a result of further PV-system installations. Particularly the high simultaneity of the power production peaks in neighbourhoods with a lot of solar are of concern. The growing risk of local breaches of the allowed voltage ranges implicate the need for additional grid investments. Fluvius states that the necessary investments in the short term can be absorbed within current budgets. Nevertheless, they state that the pressure on budgets is continuously rising, suggesting that they might not be sufficient in the near future. The magnitude of these investments is not further elaborated upon in the report.

3.2.6 Finland

Studies	Investigations related to the topic	Main findings
Fingrid (2019) [31]	Grid development plan	North-south capacity of 10-14 GW in 2035 and 14-29 GW in 2045, and plus new cross-border connections (e.g., *Aurora Line* will increase transmission capacity SW-FI 800 MW and FI-SW 900 MW and the old Fenno-Skan 1 connection from 1989 at 400 MW can be extended until 2040)
Statnett (2021) [32]	Nordic grid development perspective	Finland is expected to build 3,700 km of lines • 2,300 km of 400 kV • 1,400 km of 110 kV and • 41 new substations • 21 modernised substations • 15 extensive refurbishments • 21 expansions All substations' additions, modernisations and extensions are for 400 kV and 110 kV levels. Further details are not provided in that regard. Besides traditional grid reinforcement investments, increasing system flexibility will help to ease the load on the grid via demand response, power-to-x, storage and V2G.
Electricity Market Act § 52	Distribution network development plan	The amendment demands that DSOs' development plan shall include a plan for "the possible use of flexibility in

(amendment 15.7.2021) [33]		electricity consumption, electricity storage, energy efficiency measures of the distribution system operator and other resources as an alternative to expanding the transmission capacity of the distribution network”
Lassila et al. (2016) [34]	PV hosting capacity in the Finnish distribution system	If all rooftops are utilised fully, the PV installation could reach 12000 MWp, which could provide 7350 MW peak power on a sunny day. The peak power supply is close to the spring and summer peak demand at around 9000-10000 MW. This amount of installed solar PV capacity should not pose challenges for the Finnish electricity distribution system. Main reason for the promising outlook, stated by the study authors, is the dimensioning of the network based on wintertime loads in Finland (electric heating and saunas).

Finland is expected to primarily focus on adding north-south connections to take advantage of the onshore wind resources in the north of the country. Further enhancements of the connections to the other Nordic countries are expected to continue. Besides the traditional grid reinforcement measures, Finland is also considering relying on other flexibility measures in the face of variable renewable resources, for example demand response, power-to-X, battery storage and vehicle-to-grid technologies.

3.3 Grid reinforcement costs for several countries considering future scenarios

In the coming years, large costs will be incurred to make the grid safe for the new problems and demands addressed in 3.1 and 3.2. In this section, we will now attempt to determine the costs incurred for future scenarios on the basis of several studies. For this purpose, various scenarios were calculated in the studies that attempt to determine a certain spread of costs over the years. These scenarios are either calculated by the authors of the study themselves (see Dena) or based on documents published by the federal government and the states (see grid development plan, BMWi). However, all scenarios take into account the mass of newly installed electricity generation from renewables and the expansion/new installation of the electricity grid. In general, it is shown that the cost of grid reinforcement will be high and that this cost can be significantly reduced by new technologies in the area of smart grid control or new transmission line technologies.

3.3.1 Germany

Studies	Investigations related to the topic	Main findings
Dena [2]	From different grid reinforcement scenarios broken down for the annual cost • BAS 000: Base scenario without storage expansion of 3600 km route length • FLM 000: with overhead line monitoring expansion of 3500 km and modification of 3100 km	This study offers a variety of ways to address the problem of Grid reinforcement. It also breaks down the potential costs on an annual basis (all numbers in billion €/a): • BAS 000: 0.946 • FLM 000: 0.985 • TAL 000: 1.617 • PSW: 1.017 • VSC1: 1.994 • VSC2: 2.715

	• TAL 000: Usage of Tal Conductors expansion of 1700 km and modification of 5700 km • PSW: Grid with expanded pumped storage plants of ca. 8.4 GW • VSC1: Multi-terminal operation • VSC2: Point to point connection • HYB: Large-scale direct current connection • GIL: extensive use of gas-insulated 380 kV lines for 3150 A per circuit for 3400 km	• HYB: 1.297 • GIL: 4.924 What is special about this paper is the fact that these scenarios and their proposed grid reinforcement are not mutually exclusive. One option, for example, would be to combine overhead line monitoring (FLM 000) and the further expansion of pumped storage power plants (PSW)
BMWi [1]	Through different scenarios this paper shows a broad range of possible costs for the grid reinforcement and a yearly expansion need in € and km. Further it shows the localization of the need grid expansion.	The expanded requirements for the electrical network make it necessary to elongate the Grid by between 130,000 km (EEG 2014) and 280,000 km (Bundesländer). This would lead to costs between: • 23 Billion (EEG 2014) • 28 Billion (NEP) • 49 Billion (Bundesländer) This data can also be presented as an annual value in percent and in km for the different grid levels. Low voltage grid • 0.4% or 4,000 km (EEG 2014) • 0.7% or 7,000 km (federal states) Medium voltage grid: • 1.0% or 4,500 km (EEG 2014) • 1.8% or 9,000 km (federal states) For the localization for the grid reinforcement shows that 60 % of low voltage grid expansion need is located in southern Germany while the expansion need for the medium Voltage grid is spread evenly between all regions with no outliers. As for the high voltage grid the bigger part of reinforcement need with 39 % is in northern Germany.
Hesse [3]	This paper explores 3 scenarios for two different timespans (2024 and 2034), with the Status Quo 1,77 GW (PV)	The accumulated cost for the overall grid reinforcement cost for the target years of 2024 and 2034 for all 3 scenarios: Target year 2024: • 420 Mio € (Scenario 1)

	• Scenario1: the state doesn't manage to implement what was planned (PV 2.4 GW 2024 and 2.7 GW in 2034) • Scenario 2: the state does most of what it set out to do (PV 3.0 GW 2024 and 4.65 GW in 2034) • Scenario 3: The state manages to implement even the ambitious projects (PV 3.6 GW 2024 and 6.6 GW in 2034)	• 570 Mio € (Scenario 2) • 760 Mio € (Scenario 3) Target year 2034: • 630 Mio € (Scenario 1) • 1050 Mio € (Scenario 2) • 1520 Mio € (Scenario 3) This cost can be broken down for the different voltage level. **High-voltage grid**: • 2024: o €120 million (Scenario 1) o €170 million (Scenario 2) o €248 million (3) • 2034: o €207 million (Scenario 1) o €314 million (Scenario 2) o €494 million (Scenario 3) **Medium-voltage grid**: • 2024: o €122 million (Scenario 1) o €180 million (Scenario 2) o €224 million (Scenario 3) • 2034: o €184 million (Scenario 1) o €320 million (Scenario 2) o €427 million (Scenario 3) **Low-voltage grid**: • 2024: o €80 million (Scenario 1) o €100 million (Scenario 2) o €120 million (Scenario 3) • 2034: o €125 million (Scenario 1) o €200 million (Scenario 2) o €280 million (Scenario 3)
Baden-Württemberg [4]	This Study shows the estimated Grid reinforcement cost for the different scenarios as well as the localization of this investment need depending on the Voltage level.	Costs of grid expansion in Baden-Württemberg (in € billion): • Basis: 2,69 (NEP 1) and 2,47 (NEP 2) • Adjustable local network transformers: 2,57 (NEP 1) and 2,35 (NEP 2) • "Capping of load peaks": 2,06 (NEP 1) and 2,01 (NEP 2) • "MARKET": 2,83 (NEP 1) and 2,57 (NEP 2) • "Grid": 2,68 (NEP 1) and 2,45 (NEP 2) • "Sector coupling": 3,23 (NEP 1) and 3,48 (NEP 2)

		The costs for grid reinforcement can also be expressed in €/inhabitant in the different scenarios:
		• NEP 1:
		  ○ High Voltage Grid: 62
		  ○ Medium voltage Grid: 157
		  ○ Low voltage Grid: 31
		• NEP 2:
		  ○ High Voltage Grid: 54
		  ○ Medium voltage Grid: 141
		  ○ Low voltage Grid: 33
		• NEP 3:
		  ○ High Voltage Grid: No reliable statement possible
		  ○ Medium voltage Grid: 170
		  ○ Low voltage Grid: 49

Bavaria [5]	This study analyses the need to expand the Bavarian power grid. This section analyses the costs for the expansion of the power grid. This study also draws its figures from the German government's Network Development Plan (NEP).	At the time of writing, the cost of the Bavarian network upgrade is estimated at 1.3 billion € by 2022. This figure is derived from various grid reinforcement projects: • Thuringian power bridge (grid expansion) 46 million € • Increase in interconnection capacity between Germany and Austria (network upgrade) 138 million € • Mecklar - Grafrheinenfeld (network expansion and reinforcement) 188 million € • Redwitz - Schwandorf (grid reinforcement) 265 million € • HGÜ-connection to Grafenrheinfeld (grid expansion) €56 million • Grid reinforcement and expansion in Bavarian-Swabia 23 million € • HGÜ-connection between Saxony-Anhalt and Bavaria (grid expansion) 630 million €

The costs for the whole of Germany will be in the range of several 10 billion €. It is difficult to generalise the costs for the individual federal states, but they will be in the 3-digit million to single-digit billion range. To reduce the costs, it is possible to use new technologies and network principles. Especially through the use of new smart grid network control, costs can be saved massively, be it through peak capping, by a few percent, more precisely 1 to 3 %, expansion costs in the double-digit % range. Other possibilities in this area are expanded storage options, intelligent metering systems (smart meters), which include the precise monitoring of electricity consumption and generation. In conjunction with expanded storage systems, we usually have to look in the direction of a coupling of the energy networks. This means an overlapping of heat, gas and electricity generation with the help of power-to-heat or power-to-gas systems. The aspect of increased demand because of more e-mobility should not be ignored as a form of storage capability for PV systems.

3.3.2 France

Studies	Investigations related to the topic	Main findings

ADEME [35]	Boundaries of renewable power generation, including grids aspects for a 100% renewables-based electricity mix.
	
	Based on a scenario from the state agency for environmental and energy management.
		This study uses some of the assumptions from the long-term scenarios prepared in 2012 by ADEME and published in "ADEME Energy Transition Scenarios 2030-2050" in 2013.
		
		In the baseline scenario, the total annual cost is €50.1 billion, of which:
		• 65% is renewable energy costs.
		• 8% is for storage.
		• 27% for the network:
		  ○ 23% is for transmission and distribution network costs.
		  ○ 4% is for the 400 kV network.
		
		With a closer look on specifics network costs for transmission and distribution:
		• €11.1 billion fixed portion
		• €2.2 billion variable portion
		
		The report offers added costs to the baseline scenario on different factors:
		• The public acceptance
		• The variation of the demand
		• The complexity of network reinforcement

PPE [8]	Orientations and priorities of action of the public authorities for the management of all forms of energy in the territory (PPE).	The network transformation strategy presented by RTE (ten-year network development plan (SDDR) [25] in September 2019 is based on the use of flexible solutions to limit, where possible, investment in infrastructure. This results in an investment trajectory that should approach €2 billion per year between 2021 and 2025. The share of expenditure in the electricity transmission network remains around 10% of the total annualised costs of the electricity system. In relation to production (+92 GW of renewable energy), the accommodate cost of the grid to renewable energy remains limited by 2035. The costs of grid adaptation represent 3 to 4 €/MWh (for a cost per MWh between 58 and 64 €, which should continue to decrease between now and 2035 as Covid and geopolitical situation wasn't taken into account in the report) depending on the proximity of the existing grid (for a cost of €44/MWh for the last call for tenders).

RTE (Schéma décennal de développement du réseau) [25]	Electrical decennary grid scheme	In the PPE scenario [8], the share of expenditure on the electricity transmission network remains at around 10% of the total annualised costs of the electricity system, which amount to around €50 billion per year. In addition, the TSO mentioned that the costs of creating new facilities are shared by all producers connecting under a given scheme.
RTE [7]	Analysis of the future French energy share	In 2019, RTE published its ten-year network development plan (SDDR) [25], which has since been validated by the Minister and the CRE. With an investment of €33 billion over 15 years, it aims to bring the network up to the level required to accommodate the PPE mix and to undertake the renewal of infrastructure, some of which was built in the aftermath WW2. The investment is thus estimated at €61 billion over the period 2021-2035 to integrate variable and non-controllable production for the development of distribution networks carried by Enedis (French DSO).

The integration of renewable electricity production assets implies an adaptation of the electricity grid. This is in parallel to the renewal of the existing ageing infrastructures. The electricity transmission system operator has presented its strategy to anticipate the future of the French network. The result is an investment trajectory that should approach €2 billion per year between 2021 and 2025.

Several complementary studies challenge this amount with different assumptions. The magnitude of the cost remains in the double-digit billion range.

3.3.3 Spain

Studies	Investigations related to the topic	Main findings
Electric Transmission Network Development Plan 2021-2026 [10]	Design of the future Spanish transmission network intending to integrate massive new renewable generation, removing structural constraints.	Based on the set of actions defined to reinforce the national networks (with a limit investment value of €5,704 M€), the largest volume of investment, about 33% (1,870 M€), corresponds to the integration of renewables and resolution of technical congestions, in line with a planning focused on the adaptation of the transmission network to facilitate the process of decarbonization and the massive implementation of renewables in the system.

	Development and reinforcement of interconnections in order to achieve a renewable integration level in accordance with the objectives set at European level.	The investment cost specified in the development plan for 2021-2026 allocates 1,193 M€ for the reinforcement of the international interconnections.
Economic, employment, social and public health impact of the integrated national energy and climate plan 2021-2030 [36]	Economic impact of the energetic and climatic planification designed for Spain by 2030	The total required investment reaches 241,000 M€ for the period 2021-2030. Out of this amount, 196,000 M€ are considered as additional investment in comparison with the current trend. It is estimated that the 80% of the investment will come from private entities, while the remaining 20% from the public sector. The sharing of these investments will be: 35% for energy efficiency, 38% for renewables, 24 % network and planification and 3% for other measures.
Order IET/2659/2015 [37]	Regulated costs for grid reinforcement - Transmission level	The Order IET/2659/2015 specifies the investment and operation and maintenance reference unit values per item of fixed assets of the electricity transmission facilities
Order IET/2660/2015 [38]	Regulated costs for grid reinforcement - Distribution level	The Order IET/2660/2015 specifies the investment and operation and maintenance reference unit values per item of fixed assets of the electricity distribution facilities. Moreover, unit values of remuneration for other regulated tasks that will be used in calculating the remuneration of electricity distribution companies are also included in the Order.

3.3.4 Austria

Studies	Investigations related to the topic	Main findings
Association of Austrian Electricity Companies (2020) [39]	Grid Calculations and Influence of the Developments of Electromobility and Photovoltaics on the Austrian Electricity Grid divided in 3 scenarios: EV10, EV30 and **PV2030**	On the basis of the data collected in this study from the individual DSO´s in the federal states, it is currently assumed that the **PV2030** scenario led to additional investment costs for Austrians TSO´s and DSO´s of about **€2.8 billion.** This is due to the planned control investment costs of €10.6 billion an increase of about **27 %.** The additional costs arise in the high, medium and low voltage (NE 3-7). No additional costs are incurred in extra-high voltage (NE 1-2).

3.3.5 Belgium

Studies	Investigations related to the topic	Main findings
Imperial College London & PV Parity "Grid Integration Cost of Photovoltaic Power Generation" [40]	Direct Costs analysis related to grid impact of photovoltaics by an expert team at Imperial college London and PV Parity	Finding costs for grid improvements for further solar integration in Belgian grids are hard to come by. This study from 2013 is one of the only ones quantifying the costs. Their simulations show that with an 18% penetration level of PVs the additional distribution network cost would be between €0.5/MWh and €8.7/MWh. In this scenario the potential demand response services could reduce this cost from the suggested €8.7/MWh to €6/MWh.

3.3.6 Finland

Studies	Investigations related to the topic	Main findings
Fingrid (2021) [41]	Cost estimation for the carbon neutral Finnish grid by 2035 in 4 scenarios: 1. Power to export 2. Climate-neutral growth 3. Windy seas 4. Solar and batteries	All scenarios include a 2 b€ base expansion, mainly increasing transmission north-to-south (does not consider the grid connection cost of offshore wind). The investments include further investments in new 400 kV lines and new cross-border connection, ranging between 0.25 b€ to 1.55 b€ and 0.25 b€ and 0.9 b€, respectively. Solar and batteries scenario with lots of decentralised solar power and BESS results in lowest grid investments needed at 2.6 b€

Grid reinforcement costs may vary depending on the path that Finland chooses for the transition in the next decade but 2 b€ expansion is expected to take place regardless of the path. Interestingly, the solar PV and batteries heavy scenario offers the lowest grid investment needed, possibly related to the fact that the majority of the population already lives in the area of the country with most solar irradiation.

4 REGISTRATION, MEASUREMENT AND MANAGEMENT OF DISTRIBUTED PV (TRANSPARENCY)

4.1 Registries available in different countries

4.1.1 Germany

a) General Information / Background

In Germany PV plants have to be registered in two ways as the following table shows:

Registries	Data to be registered	Responsible body
a) MaStR	Master data of PV-plants	Plant operator
b) Register at grid operator	Information about the plant, the owner and the operator	Plant operator/ electrician for implementing

Markstammdatenregister (MaStR):

The MaStR is a governmental register for master date of the electricity and gas market. Since 31.01.2019 all players in the electricity and gas market are required to register themselves and their power plants in the MaStR. The EEG (Erneuerbare-Energien-Gesetz) obligates operators of a PV plant to register in the MaStR to get the compensation defined in the law.

The Marktstammdatenregisterverordnung (MaStRV) manages which plants have to be registered. In addition, the decree manages the deadlines for the registration.

Register at the grid operator:

The EEG stipulates mandatory inclusion by grid operators. The installation of the systems must be carried out according to different specifications depending on the capacity and the connection point with the distribution network.

For the connection of generation plants < 135 kW, the VDE application rule VDE-AR-N-4105 “Generating plants on the low-voltage grid – minimum technical requirements for the connection and parallel operation of generating plants on the distribution grid” applies.

For the connection of generation plants ≥ 135 kW, the VDE application rule VDE-AR-N 4110 -Technical rules for the connection of customer plants to the medium-voltage grid and their operation (TAR Medium Voltage) applies.

b) Databases Parameters

Markstammdatenregister (MaStR):

In the MaStR, all registered units, locations and market-players are visible. In the public overviews, data can be exported as csv File. Data of natural persons ranked as confidential are not public. In the following table, you can see an overview of the master data for PV-plants and the difference between public and confidential data [42].

Table 9: Available data parameters of Marktstammdatenregister [43]

Master Data	public	confidential
MaStR-no. of the unit	√	√
Name of the unit	√	√
Operation status	√	√
Energy carrier	√	√
Gross/net output	√	√
Date of initial operation	√	√
Date of registration	√	√
Federal state	√	√
Postal code, city	√	√
Street, house number	-	√
Coordinates	-	√
Number of solar modules	√	√
Orientation of modules	√	√
Position of the unit	-	√
Name of the plant operator	-	√
Full-/half-feed-in	√	√
Name of the grid operator	√	√
Voltage-level	√	√

In the MaStR only master/static data are registered. Dynamic data e.g. actual performance data cannot be recorded in the register.

Register at the grid operator:

In Germany, the application rule VDE-AR-N 4105:2018-11 specifies the technical requirements for the grid connection of generation plants and energy storage systems.

In the appendix E “Generation plants on the Low voltage network – Forms“ the form for the filling of application and the form for the data sheet for generation plants are found.

The form for the filling of application includes:

- Address of the plant
- Address of the owner
- Address of the operator
- Plant builder (electro technical company)
- Information about new plant, expansion or deconstruction
- Information if additional documents are attached

The form for the data sheet for generation plants includes:

- Address of the plant
- Type of energy

- Type of BHKW (combined heat and power systems)
- Information about the producer and the type
- Power of the unit (active power, apparent power)
- Mode of operation
- Reactive power compensation

The grid operator investigates the possibility of connection at the suitable grid connection point. In addition, he performs a network compatibility check.

c) Data Acquisition

For all installations, operators must register themselves and enter the installation data. All data must be kept up to date. The electricity and gas network operators have to register their company in the MaStR. They have to check the data of the plants connected to their grid and supplement them. The grid operators are obliged to take the registrations in the MaStR into account in their billing procedures. [44]

Registered users can access the data of the MaStR via a standardised web interface.

d) Feed-in management

The generation plant must be provided with a technical device in accordance with Section 9 (1) EEG 2017 (feed-in management). For photovoltaic systems below 100 kW, Section 9 (2) EEG 2017 applies [45].

Photovoltaic systems with an installed capacity of more than 30 kWp and no more than 100 kWp must meet the technical requirements for feed-in management in accordance with Section 9 (2) No. 1 EEG 2017. For this purpose, a simplified feed-in management based on ripple control technology is provided. Photovoltaic systems with an installed capacity of 30 kWp or less must also meet the technical requirements for feed-in management in accordance with Section 9 (2) No. 1 EEG 2017. Alternatively, their active power feed-in can be limited to 70 percent of the installed capacity. [46][47]

4.1.2 France

a) General Information / Background

All power plants must be registered in multiple databases following the milestones of the project development:

- Response to calls for tender
- Environmental impact
- Construction permit
- Grid connection demand
- Purchase agreement

The plant owner must register his assets to achieve the milestones. The proprietary is always responsible for the registrations and any information is destined to public dissemination.

There is no synergy in the data acquired through the different services. To anticipate the future energy share and help the renewable energy development. The SER (Syndicat des Energies Renouvelables) and the FEE (France Energie Eolienne), two French unions, often aggregate the datasets. TSO and DSO also offer their production balances.

b) Databases Parameters

Table 10: Main data registered in the French databases

Data designation	DSO	TSO	Purchase agreement	Utilities
Plant owner	√	√	√	√
Feed-in start date	√		√	
Peak power	√	√		
Production			√	
Electrical network				√
Contact	√	√		
Field and forecasted production		√		
Localization	√	√		

c) Data Acquisition

Most of the document is digitalized and based on a paperwork model. The documents are available on the services website and can be uploaded after filling.

The platforms are as follows:

- Response to calls for tenders: CRE website
- Environmental impact: DEPOBIO
- Construction permit demand: Each community must propose a platform to upload the construction permit demand.
- Grid connection demand: DSO website
- French TSO: AERO
- Purchase agreement: EDF OA website

In addition, it may be possible that the INSEE (National Institute of Statistics and Economic Studies) ask to the plant's owner information by annual surveys. On digitalized demand basis without platform.

4.1.3 Spain

a) General Information / Background

1) According to the Royal Decree 1955/2000, which regulates the transmission, distribution, retail, supply activities and the authorization of electric energy facilities [48], all electrical energy production facilities authorised for the sale of electrical energy in Spain must be registered in the **Administrative Register of Electric Power Production Facilities (RAIPEE**). Such registration is an indispensable requirement for the participation in the electricity markets and the signing of bilateral contracts. Since March 2022, also the storage facilities which can inject energy into transmission or distribution networks have the same obligation as any other production facility. This register is managed by the Spanish Government, and it is only partially publicly available.
2) In addition, according to the Royal Decree 244/2019 [49], which regulates the administrative, economic and technical conditions of the electric energy self-consumption, the self-consumption installations (i. e. installed capacity < 100 kW) must also be registered in the **Self-consumption**

Administrative Register, which is very simple being its main objective the statistical monitoring of the self-consumption deployment. The responsible of the register is the Spanish Government and the registration process can be made digitally.

3) **Iberian Market Operator (OMIE)**: In order to participate in the wholesale electricity markets, day-ahead and intraday, the participants must be registered in the market operator's database. For such participation, sale/acquisition units must be registered by each participant. The resolution [50], which approves the operating rules of the day-ahead and intraday markets, establishes the information provision requirements in its rule number 12. The information gathered in this registration is only partially publicly available.

4) **Structural database of the electrical system**: According to the system operator's operating procedure 9.0, information exchange by the system operator [51], the system operator is responsible for collecting, maintaining and updating the structural data of the electrical system. The installations connected to the transmission or observable networks, as well as the production facilities, consumers and elements of control and protection that the system operator needs in order to develop its functions, must provide information to this database. The observable network is made up of facilities whose topology and control variable measurements must be known in real time by the system operator in order to operate the system in a proper and secure manner. The information included in this database is confidential.

b) Databases Parameters

1) Administrative Register of Electric Power Production Facilities (RAIPEE) [48]: The information to be provided in this registration is mainly related to the ownership of the production facility and data of the production unit (e. g. technology, installed power, net capacity, voltage level of the connection point, node, etc.)

2) Self-consumption Administrative Register, according to RD 244/2019 [49]. The main data registered are: i) Ownership and location of the installation, ii) supply point (e. g. contracted power, voltage level of the connection point, DSO or TSO of the connection point, etc.), iii) generation facility (e. g. technology, generation installed capacity, etc.), iv) storage facility if applies (e. g. installed capacity, maximum stored energy, etc.), v) self-consumption typology (e. g. individual/collective)

3) Iberian Market Operator database [50]: The main data included are: i) sales/acquisition unit code (defined by the market operator), ii) Description and type of the sale/acquisition unit, code of the electrical system in which the unit operates (Spain/Portugal), iii) maximum upward and downward gradient in MW/h with one decimal.

4) Structural database of the electrical system. The information to be provided is available in the Annex I of the system operator's operating procedure 9.0, *information exchange by the system operator* [51]. General information is required (e. g. address, ownership, identification code in the RAIPEE, installed capacity (MW), nominal power (MW), control capacity of reactive power, etc.). In addition, based on each technology, specific data are required (e. g. building/ground installation, number of solar tracking axes) and necessary data for the performance of dynamic studies by the system operator are also required. In section 4.1.2 of the Annex I the requirements for PV installations are detailed (e. g. information about response time of the voltage control in permanent regime, technical ability to withstand transitory overvoltage, etc.). When the installation participates in the ancillary services, additional information is required.

c) Data Acquisition

1) Administrative Register of Electric Power Production Facilities (RAIPEE): The documentation and information for this register must be sent by the generation unit to the regional government. Once

the production unit acquires the status of market agent, the definitive registration is sent to the Directorate General for Energy Policy [48].

2) Self-consumption Administrative Register [49]: The inscription of self-consumption systems in the register is carried out ex officio by the regional government if the capacity of the installation is below 100 kW. The Directorate General for Energy Policy incorporates within its Administrative Register of Electric Power Production Facilities, those generation installations < 100kW which are registered in the self-consumption register.
3) Iberian Market Operator database: The market operator has established an electronic procedure to attach the required documentation. In order to ease the process, the market operator has the document "Market Access Guide", available on its website [50].
4) Structural database of the electrical system [51]. The Spanish System Operator, Red Eléctrica de España (REE), determines the support and the templates for the information exchange. The information included in this database is confidential.

4.1.4 Austria

a) General Information / Background

Register DSO

In Austria, for a new PV project, a request must be submitted to the DSO in order to obtain a grid access point. According to ElWOG 2010, generation plants based on renewable energy sources with a bottleneck capacity of up to 20 kW shall be connected to the distribution grid upon notification to the distribution system operator. A complete request shall contain at least the following information:

- Name and address of the network user and address of the installation to be connected
- In the case of new installations: site plan
- Desired start of the feed-in
- Maximum capacity of the installation in kW corresponding to the actual capacity needs of the grid user
- Number and location of meter system
- Plant and operation type
- Predicted annual quantity in kWh

Ökostromanlagenregister

The "Ökostromanlagenregister" has included in this register all renewable energy plants that have a valid contract with the "Ökostromabwicklungsstelle (ÖMAG)" under Parts 3 and 4 of the "Ökostromgesetz 2012" as amended. The "Ökostromanlagenregister" is obliged to maintain a database for automation-supported data processing. This register allows grid operators, E-Control and the energy ministry access to data in form of exportable data. Plant operators can acquire their own data from this register to. [52]

Stromnachweisdatenbank

With Directive 2001/77/EC of 27 September 2001, the European Union for the first time set national indicative targets to promote the generation of renewable energy. These targets and instruments were transposed into national law in Austria by the "Ökostromgesetz", which was published on 23 August 2002 and came into force on 1 January 2003.

Installations for the generation of energy from renewable sources which are connected to the public grid shall be registered in the “Herkunftsnachweise” database of the regulatory authority by the installation operator, an authorized representative of the installation or by a third party appointed by the installation operator until the installation is commissioned. In the case of existing installations, registration shall be carried out within three months of the entry into force of this Act. [53]

Table 11: Available registers in Austria

Registries	Data to be registered	Responsible body
Register DSO	Information about plant, capacity, owner	Plant operator/ electrician for implementing
Ökostrom-anlagenregister	Database for green power plants according to ÖSG 2012	Ökostromabwicklungsstelle
Stromnachweis-datenbank	Guarantees of origin in accordance with EU Directive 2009/28/EC	E-Control (Regulator)

b) Databases Parameters

Table 12 Master Data of Ökostromanlagenregister

Master Data	public	confidential
Plant name and plant operator	√	√
Commercial data	-	√
Production capacity	-	√
Type of plant and congestion management	-	√
Production times and place	-	√
Used energy source	-	√
Type and amount of invest funding	√	√
Type and amount of other fundings	√	√
Start-up date of the plant	-	√
Shut down date of the plant	-	√

c) Data Acquisition

The data for the subsidized green power plants are entered into the database by the eco-balance group manager (Öko-BGV), and the “Herkunftsnachweise” are automatically distributed to the traders in accordance with the provisions of the Green Electricity Act.

A special case are green electricity quantities promoted by the Ökobilanzgruppenverantwortliche (OeMAG). These are entered directly into the database (Ökostromanlagenregister) by OeMAG. After transmission, the “Herkunftsnachweise” are automatically attributed to the electricity suppliers in the amount allocated by the Öko-BGV schedule.

4.1.5 Belgium

a) General Information / Background

All PV system owners are obliged in Belgium to register their PV installations. For installations with a nominal power larger than 10kVA, a grid study needs to be requested first before connecting the system to the grid. For smaller PV installations, a grid study is not carried out, but the grid owner is still obliged to register the PV system when it is becoming operational.

Most of the PV systems in Belgium are connected to the distribution electricity grid. The distribution system operator (DSO) operates a database in which the data of the PV installations are stored. In addition, the Belgian TSO uses a separate database, called PISA. Solar plants larger than 400kVA must be registered by the DSO individually in the TSO database. There is no obligation for the DSO to put in smaller plants in the TSO database, but the DSO is allowed to register these in an aggregated form.

In addition to the mentioned databases, PV data is stored in different databases regarding to different topics such as technical parameters, subsidies and ancillary services.

b) Databases Parameters

Table 13: Overview of the parameters included in PV databases in Belgium.

General information about the database	
Database for PV systems available and in operation	√
All PV systems (in the concerned region) must be registered in the database	√
Only certain systems (e. g. systems claiming a FIT or systems above a certain capacity) must be registered in the national database	-
Database is mostly available for third parties (e. g. public)	(√)
Database is strictly confidential	-

General data	
Project name e.g. (name new installation)	-
Identification number	√
County	√
City	√
Address	√
Coordinates	(√)
Type of Feed-in Tariff (FIT)	-
Operational metering data with monthly (or yearly) resolution	((√))
Operational metering data with daily (or smaller) resolution	((√))
Site data (if several databases are in place, ticks refer to most official database)	-
Type of consumer (household, industry, ...)	-
Type of system (rooftop, ground mounted)	-

Technical data	
Type of module	-
DC-power	-
AC-power	√
Inverter power	-
Inverter manufacturer	-
All modules have the same orientation (yes/no)	-
Orientation	-
Tilt angle	-
Ancillary services (yes/no)	(√)
Remote control by DSO	(√)
Remote control by TSO	(√)
Remote control by Market Parties	(√)
Remote control by others	(√)
Can be operated in islanded mode	-
Black start capable	-
Type of grid connection (injection only/ self-consumption)	-
Maximum power fed into the grid	√
Energy capacity storage if present (e.g. battery)	(√)
Inverter power (battery inverter)	(√)

(√): not available in the same database for PV (aggregated or stored in other database); ((√)): size-dependent; [data source other: own analysis from D1.2, following the table structure based on IEA PVPS task 14]

c) Data Acquisition

Every PV installation needs to be reported to the DSO [54]. Depending on the DSO the required information includes the PVZ-number, inspection report, certificate of the inverter manufacturer, etc.

4.1.6 Finland

a) General Information / Background

All power plants with a rated AC power of at least 1 MVA must be registered. Currently, there is only one PV plant in Finland belonging to this category at 4.6 MW [55]. Other PV systems are distributed systems below 1 MVA, estimated at total 288.1 MW at the end of 2020. The individual DSO documents its systems in its own databases. The databases of the DSO are not harmonised.

The Finnish Transmission System Operator (Fingrid) employs Guarantees of Origin (GO) certificates that are used to verify that the electricity was produced from renewables, nuclear, or high efficiency cogeneration plants. Fingrid maintains a list of production facilities that have GO certificates [56].

b) Databases Parameters

Currently the amount of distributed PV capacity in Finland is collected with an inquiry done by the Energy Authority (Energiavirasto) to distribution companies on a yearly basis. The rated power (capacity) is the only technical parameter that is collected.

c) Data Acquisition

The Energy Authority (Energiavirasto) publishes a regularly updated Power Plants Registry [57] where it currently lists 3 solar PV plants (as of 12.1.2022). The Energy Authority notes that it does not verify the validity of the information.

4.1.7 Summary

In all participating countries, the PV system is registered with the responsible grid operator. Since the connection to the grid very often takes place at the low-voltage level, the local distribution grid operator (DSO) is the first point of contact. In addition, there is a superordinate database in almost all participating countries, which records the entirety of all systems. This is implemented either by a database of a public institution or by the transmission system operator (TSO) of the respective country, which is especially the case in smaller countries or countries with a (still) low PV penetration.

In addition, other specialized databases have been established in many cases, e.g. for plant operators who want to actively participate in electricity trading. An explicit synchronization between the different databases is currently not regulated in any of the countries. A strategy for the implementation of a single-source data management is also not being implemented in any of the countries. Access to the collected data is mostly done by checking for a legitimate interest of the person requesting the data.

All countries have recognized the necessity and the additional benefit resulting from the detailed knowledge of the PV plants and have implemented corresponding databases or are currently in the process of implementing such databases.

Table 14 characteristics of the databases in the different countries

Parameter	Germany	France	Spain	Austria	Belgium	Finland
National database for PV systems available and in operation	√	(√)	√	(√)	(√)	-
All PV systems must be registered in the national database	√	(√)	√	-	(√)	-
Only certain systems must be registered in the national database	-	-	-	√	√	√
Database is mostly available for third parties (e.g., public)	√	√	√	?	?	√
Database is strictly confidential	-	-	-	?	-	-
Additional database at the responsible grid operator	√	√	(√)	√	√	√

The rapidly increasing number of distributed PV systems connected to the power grids require appropriate system documentation. Central databases using harmonised data models are supportive for many administrative tasks related to PV systems. In order to establish a database for PV systems, the following general recommendations are made [44]:

- Collecting all relevant PV system data within a jurisdiction into a single database offers considerable advantages. The database should be accessible by all relevant stakeholders.
- The plant owner should be owner of their own data. However, they should be obliged to register their plants in the system and to update the data according to the registry requirements. Arrangements can made to have suitable third parties undertake this task on the PV system owner's behalf – for example, installers or network businesses.
- The database should be used to reduce the administrative workload caused by DER as much as possible. Different tasks such as building permits, connection permits and subsidies shall as far as possible be administrated using the same database.
- The plant owner shall be responsible to update the database within a given time after major changes are made to the PV system, such as repowering. The data of the PV system should be updated during the entire lifetime of the plant.
- If the data of a PV plant is modified by a third party (e.g. the governmental administration updates the status of the permission process), the plant owner should get an automatic notification.
- Multi-stakeholder access to the database is recommended. E.g. DSO should have full access to the technical details of the plants in their grid area. A limited amount of data such as system size and community of installation should be available to the public. The data should be available in an appropriate form for research purposes.
- Privacy and data security issues shall be properly assessed and addressed. Every user of the database shall only have access to those items in the database, which are needed in order to fulfil specific tasks. The database structure, contents and requirements should be developed collaboratively through consultation with industry, policy makers and other relevant stakeholders.

4.2 Developments taking place (measurement and data management concepts)

4.2.1 Germany

Summary: Smart meter rollout, projects available

On September 2, 2016, the Metering Point Operation Act (Messstellenbetriebsgesetz, MsbG) came into force, bundling the requirements for metering and metering point operation. It regulates technical requirements, financing and data communication and thus lays the foundations for the introduction of **smart metering systems**. A smart metering system consists of a modern **metering device** and a **communication unit** (smart meter gateway). The smart meter gateway enables the smart metering systems to record, process and securely send consumption-relevant metering data. [43]

The smart meter rollout started by 24.02.2020. The basic metering point operator is responsible for the installation, technical operation and maintenance of electricity meters in its area in accordance with Section 3 of the German Metering Point Operation Act (MsbG). However, there is an option of choosing a different, competitive metering point operator. This metering point operator must meet the requirements for proper metering point operation. [43]

According to the ideas of the BMWi, modern metering devices should replace existing electricity meters in all households by 2032. The additional smart meter gateway, which can be used to upgrade modern metering equipment to smart metering systems, is generally only to be installed in consumers with an annual electricity consumption of over 6,000 kilowatt hours. Most private households are not affected by this, as they have lower electricity consumption. However, metering point operators have the option of also using smart metering systems for customers with an annual electricity consumption of less than 6.000 kilowatt hours, as long as they adhere to very strict price specifications. [43]

4.2.2 France

As a response to the impetus of the European commission regarding the metering systems, the French government amended the guidelines in the 2015 law «Transition énergétique pour la croissance verte».

The national energy regulatory commission, CRE (Commission de Régulation de l'Energie) started a plan to develop a smart meter called « Linky ». The project started in March 2010 with the first implementations and the objective of 95% of penetration by 2020. On the demand of the State agency for environmental and energy management, ADEME (Agence de l'environment et la maitrise de l'énergie) and under the control of the CRE, Enedis, the DSO responsible for the 95% of the electricity distribution activities is responsible for the implementation and ownership of the rollout.

The CRE assessed the 31 December 2021 that 90% of household were equipped with the Linky smart meter [58].

Linky is essential to the French energy transition by offering a more accurate view of the electricity network for the DSO with a better knowledge of consumption and production. It also facilitates the renewable energy development mainly by permitting the easiest grid connection for domestical PV installation. Also, by encouraging sobriety through a daily vision of consumption and invoicing to customers.

The development for the rest 10% of household is taking place and it's the main objective for 2024.

The Linky smart meter is developed and tailored for small power and domestic needs. Enedis (French DSO) provide a special smart meter for industrial uses called DEIE (Dispositif d'Echange et d'Information d'Exploitation).

Every power producer with a noticeable impact on the grid must install the DEIE on the plant. The aim of the device is to allow the real time transmission of information and request from the DSO, for a viable and responsive monitoring of the grid.

The main information is for example:

- Voltage
- Active power produced
- Reactive power produced
- Plant availability
- Plant connection to the grid

However, the exchange between the DSO and the DEIE are in no way intended to replace the monitoring of the installation by the proprietary. Only the tele-actions to protect the grid or the installation are, if necessary, carried out directly by Enedis.

The information provided by the DEIE is crucial as it is the reference for the billing of energy in the framework of the purchase obligations in France.

The development of the new version of the DEIE is taking place. The eDEIE is the new interface for renewable assets connected to the grid. It should replace the DEIE in the future.

The eDEIE is basically design with the same features but with additional objectives:

- Cybersecurity

- Short circuit power monitoring
- Better overview of the plants with:
  - availability of the plant component
  - theoretical maximum power production in real time (in case of limitation)

Regarding the developments taking place in the registration field, the French government is willing to improve the processes.

POTENTIEL is a platform intended to simplify the administrative milestones of the developers of ENR projects. The aim is to speed up the processing of applications and enable monitoring of the achievement of PPE[8] targets by centralizing all the stakeholders of PV projects around a unique tool. The platform is in beta test and under development.

4.2.3 Spain

In Spain, as of July 2007, the metering equipment to be installed for new electrical energy supplies up to contracted power < 15 kW, and those to be replaced for the old supplies, must allow measurement discrimination on an hourly basis, as well as remote management.

In accordance with this, the Unified regulation for the measurement points of the electrical system [59],, incorporates new issues related to tele-management in order to allow the development and adaptation of measurement systems and equipment. Depending on the connection point, the measurement equipment, as well as the registration and connection requirements, will be different.

The metering points considered in the Spanish electricity system are defined in article 7 of the Regulation [59] based on the type of border point; generation, consumer or others. Specifically, the generation/demand facilities are classified as follows according to the nominal apparent power/contracted power:

	Generation	Demand
Type 1	Nominal apparent power ≥ 12 MVA	Contracted power ≥ 10 MW
Type 2	450 kVA ≤ Nominal apparent power > 12 MVA	450 kW ≤ Contracted power > 10 MW
Type 3	50 kVA < Nominal apparent power > 450 kVA	50 kW < Contracted power > 450 kW
Type 4	15 kVA < Nominal apparent power ≤ 50 kVA	15 kW < Contracted power ≤ 50 kW
Type 5	Nominal apparent power ≤ 15 kVA	Contracted power ≤ 15 kW

Each type of measurement point is linked to a basic measurement equipment with different measurement registration requirements, which are defined in article 9 of [59]. Some of such requirements are detailed below, specifically for generation installations:

Type 1 + Type 2 + Type 3:

- Communication devices for remote reading
- Appropriate communication channel defined in complementary technical instructions (RS- 232 or optocoupler)
- Power control by six maximeters with an integration period of 15 minutes
- Recorder with capacity to parameterize integration periods of up to 5 minutes

Type 4:

- Communication devices for remote reading

- Appropriate communication channel defined in complementary technical instructions (optocoupler)
- Power control by six maximeters with an integration period of 15 minutes
- Six registers of active energy + six of reactive energy + six of power
- Recorder with capacity to parameterize integration periods of up to 1 hour, as well as to record and store the active and reactive energy hourly curves for a minimum of 3 month

Type 5:

- Appropriate communication channel defined in complementary technical instructions (optocoupler)
- Ability to control the demanded power both through maximeters and other elements with a power limitation function
- Measurements with time discrimination, ability to manage six scheduling periods
- Recorder with capacity to parameterize integration periods of up to 1 hour, as well as to record and store the active and reactive energy hourly curves for a minimum of 3 month.
- This metering equipment must be integrated into a telemanagement and remote metering system implemented by the entity in charge of the corresponding reading.

The equipment types 3 and 4 located at low voltage may be integrated into a telemanagement and remote metering system. Provided that the equipment meet, in addition to the specifications of telemanagement and telemetry system, all the established requirements for measurement points types 3, 4 and 5 (whichever is more demanding in each case).

The Distribution System Operators are in charge of reading the metering equipment of generation facilities types 3, 4 and 5, being the System Operator in charge of the types 1 and 2.

4.2.4 Austria

In course of the legislative package (Artikel 13 der EU-Richtlinie 2006/32/EG (EDL 2006/32/EG)) an amendment of the Austrian “Energiewirtschafts- und Organisationsgesetz” (ELWOG) was done to allow a rollout of smart meters till 2020 (goal 80% smart meters). It was documented that the ministry for economics has to fulfil an economic analysis before the smart meter rollout can be started. The Austrian E-Control was assigned with the regulative affairs, defining the technical requirements and the regulations for consumer access.[60]

Three regulations were developed in this process:

- Datenformat- und Verbrauchsinformationsdarstellungs VO 2012 (DAVID-VO 2012)
- Intelligente Messgeräte-AnforderungsVO 2011 (IMA-VO 2011)
- Intelligente Messgeräte Einführungsverordung (IME-VO) (amendment 2017)

DAVID-VO 2012

The daily gathered end-user data must be transmitted from the grid operator to energy producer monthly. The end-user can access his data from the grid operator online, including the electric power consumption and load curves.

IMA-VO 2011

This regulation describes the technical requirements. An abstract is given below:

- Bidirectional communication
- Power consumption has to be saved as 15-minutes average
- Internal storage for 60 days
- Data transfer once a day (latest 12:00 pm of the following day)

- Communication interface for at least four external power meters

IME-VO

The IME-VO regulates a stepwise rollout of smart meters, aiming a 95% quote within end of 2024. Grid operators are obliged to reach a 40% quote with end of 2022. Load profile meters are also counted as smart meters.

4.2.5 Belgium

The EU legislation concerning smart meters outlined in the Energy Efficiency Directive and the EU Internal Market in Electricity was the starting point for amendments of the Belgian law [61]. Due to the structure of the Belgian State and the distribution of competences, the research regarding the roll out of smart meters and legislative amendments, were carried out by the three regions: Flanders, Brussels and Wallonia. In all regions the DSOs are responsible for the installation of the smart meters, respectively Fluvius, Sibelga and Ores.

On the 8th of May 2009, the Flemish Energy Decree described the roll-out and installation of digital meters. The Decree regulates the installation of smart meters or replacement of old meters, e.g. in case of new buildings and the connection of a new decentral production installation [62].

On the 19th of July and the 20th of July 2019 the Walloon government and Brussels government made amendments to corresponding laws for the roll-out of smart meters in their regions [62].

The actual roll-out of smart meters started in Flanders on the 1st of July 2019 and by the end of 2021, Fluvius had installed more than 1 300 000 smart meters. In Wallonia the number of installed meters was approximately 39,000 according to ORES [63].

4.2.6 Finland

"Fingrid [the Finnish TSO] has been participating together with the Åland TSO (Kraftnät Åland) and the Estonian TSO (Elering) in a Smart Grid deployment project called "CrossFlex project" included in the 4th PCI-list. The project's overall aim is to support renewable energy systems integration and increase security of supply in mainland Finland, the Åland Islands and Estonia by cross-border provision of flexibility services provided by distributed generation connected to both distribution and transmission networks.

Fingrid has also been participating together with TSOs from Estonia, France, Latvia and Denmark and DSOs from Estonia, Latvia and Lithuania in the Data Bridge project which is also included in the 4th PCI-list. The project aims to build a common European Data bridge Platform, to enable integration of different data types (smart metering data, network operational data, market data), with a view to develop scalable and replicable solutions for the EU."– Energiavirasto, 2020 [55]

"More than 99 per cent of consumption places in Finland had already a smart meter." – Energiavirasto, 2020 [55]

Currently, the technical requirements are being defined for 2nd generation smart meters that could allow load control capability that would enable demand response technology. - Ministry of Economic Affairs and Employment, 2018 [64]

4.2.7 Summary

All countries examined have documented the installed PV systems in databases. However, the type and level of detail of the documentation varies. This is probably primarily because the databases of the different countries are used for different purposes. It is recommended that it should be checked for which purposes the data of PV installations can be used for in each country, based on a stakeholder analysis. The database should then be structured and operated in such a way that it covers as many different purposes as is appropriate without requiring redundancy in data collection. Besides the analysis carried out of the countries involved in the project here, this Summary based also on the IEA Task14 Report "Data Model for PV Systems" [44].

The use of dynamic data gathered by smart meters such as quarter hourly, hourly, daily, monthly and annual energy yield data is in place by all participating countries at different technology readiness levels. In most countries, a smart meter rollout has already started or is currently taking place. If this is considered, the structure and size of the database will fundamentally change. On the other hand, it would enable additional benefit such as energy production monitoring, performance monitoring, availability monitoring, etc.

4.3 Evaluation of the lack of transparency in distribution networks regarding PV data and gap analysis

Currently, the integration of PV systems into distribution grids is still largely done according to a "fit and forget" approach. However, with increasing grid penetration, the fluctuating energy feed-in from PV systems poses many challenges for existing grids and possibly also for market processes.

In the past, energy was provided by a few hundred large, centralized power plants and the flow of energy was predominantly a one-way from the transmission grid of the transmission grid operators to the distribution grid of the regional grid operators and municipal utilities. However, with the increased use of renewable decentralized energy systems - primarily wind power and solar power plants - the majority of energy provision is shifting to the distribution grids. However, distribution grids were not built for this usage. The associated change in the load on the distribution grids first requires more transparency in order to gain insight into the new energy flows.

For this transparency in the distribution grid and the necessary controllability of decentralized energy systems, existing distribution grids worldwide are being converted into smart grids. The purpose of smart grids is to enable massive expansion and efficient use of distributed energy resources (DER). To support real-time monitoring and analysis of PV systems as well as (partially) automatic grid control, the use of reliable bidirectional communication technologies and an automatic control system for the integration of PV systems is crucial worldwide [65].

In the conventional electrical power system infrastructure, communication systems have played an important role in some aspects, such as operation, market transactions, security and integration of large generation and distribution systems. On the distribution side, the electric network was mainly passive, operating in a feeding load scheme, with limited interaction between the supply and the loads. This required little or no communications at all. However, the integration of DERs, such as solar PV system in distribution system or customer premises, has motivated the development of different control strategies to take advantage of distributed and controllable resources. This has highlighted the importance of last-mile communications networks as a supporting infrastructure to allow the different modes of operation of the electric distribution network.

The increasing penetration of distributed PV systems also request for a grid-scale coordinated control network. The control paradigm of current electrical power systems is slow, open-looped, centralized, human-in-the-loop, deterministic and, in worst-case, preventive. At transmission level, the energy management system (EMS) coordinates system-wide decisions based on SCADA data. At the distribution level, traditional

Volt/VAR control is designed mainly to cope with the slow variations in load. However, the increasing penetration of solar PV with rapid and random fluctuations implies the future control must be real-time and closed loop. The large-scale deployment of sensing, two-way high-speed communication infrastructure and the advanced PV inverters have provided the platform to realize the distributed, real-time closed-loop control architecture in the near future.

Currently, the deployment of communication and control systems for distributed PV systems is increasing across all countries. The public awareness on the communication and control of grid-connected solar PV systems is also rising. However, the actual development of communication and control systems for distributed solar PV systems are still in the early stage. Many communication technologies and control functions for distributed solar PV systems are still under development, ongoing standardization processes and/or in demonstration phase.

In the following, it is necessary to further detail and collect the communication and control system architecture, analyse the technology and protocols, and evaluate the best practice for different application environment. The communication technology selection and implementation is significantly affected by geographical, administrative, physical and logical reasons. The boundary conditions and transferability to the different countries' legislations should be reviewed.

The major investigations regarding the communication and control of PV distributed systems should especially focus on the last-mile communications between customer premises and utility core communication network:

- The last-mile communication and control requirements for different services, including data throughput, latency, reliability
- Last-mile communication standards, technologies, protocols and implementations for distributed solar PV integration
- Typical control architecture and strategies for distributed solar PV integration
- The data management, cyber security and other IT-related aspects of PV integration

5 TRANSFORMATION OF NETWORK DESIGN FROM HIGH-CAPACITY RESERVES TO SMART GRIDS (CONTROLLABILITY)

5.1 Background

During the last years, and due to the increasing penetration of PV plants in the generating system, several concerns have been raised regarding the impact of the replacement of traditional generators with converter-based generators.

In that sense, countries have adapted their traditional grid codes in order to account for this increasing penetration and require from the PV plants some supporting services which might enhance the grid stability in this changing scenario. In the particular case of Europe, the European Commission developed the Regulation (EU) 2016/631, which stablishes a common network code for grid connection of generators in EU and sets out the technical rules relating to the connection of new generating installations to national networks.

The mentioned regulation touches base to state the desired characteristics that a PV generator should have in order to support the grid stability and allows some margin for each specific country to adapt some of the requirements based on country specific conditions.

5.1.1 Germany

To fit the developed EU Regulation 2016/63 to specific demands in Germany, VDE FNN has enforced two changes in the respective standards for the connection of PV plants to the low- and medium voltage grid.

- According to 2016/631, PV plants connected to the MV grid require to provide LVRT ability. Because the amount of PV plants connected to the LV grid in Germany has increased immensely over the years, as it is elaborated in VDE – AR – N 4105, also PV plants to be connected to the LV grid require the LVRT ability to increase grid stability.
- To minimize load shedding in the distribution grid in the event of under frequency (LFSM-U) and thus maintaining the high quality of supply in Germany, according to VDE – AR – N 4105 and VDE – AR – N 4110, PV plants connected to the LV and MV grid must provide the ability of active power feed – in.

5.1.2 Spain

In order to regulate the connection of new generators in the Spanish grid and ensure that the newly connected PV generators support the grid stability, three different regulations have been derived from the global EU regulation.

- Orden TED/749/2020: Stablishes the grid code according to EU regulation and sets specific requisites for those requirements for which the EU regulation did not set a particular value.
- NTS V2.1: Describes the procedure to be followed to demonstrate compliance of the equipment with the grid code and the simulation models validation process.
- RD 647/2020: Regulates the connection process in order to ensure that the new grid codes are fulfilled.

5.1.3 Austria

According to § 22 Abs 2 E-ControlG the Austrian´s regulator E-Control, in cooperation with the operators of electricity grids publish a technical set of rules which control the grid connection contract within the framework of general contractual conditions for the operators of distribution or transmission grids between the grid operator and the grid user. [66]

Changes for PV compared to the previous TOR rules:

- Robustness: FRT1 capability even with LV connection; reactive current support with MV connection
- Voltage maintenance: integrated P(U) controls instead of voltage monitors
- Telecontrol: disconnection option; connection at the request of the network operator
- Main disconnection protection: integrated N/A protection according to VDE-AR 4105 also applies as automatic acting disconnecting point
- from 250 kW maximum capacity (type B):
    - Simulation parameters for studies of the static and dynamic operating behavior at the grid connection point on request of the grid operator
    - Data exchange: possibly real-time data to network operators according to Art. 40(5) SO-GL

5.1.4 Finland

Grid code specifications for power generating facilities are based on the European Network Code (European Commission Regulation 2016/631), to which the Finnish Transmission System Operator (Fingrid) has made national additions and clarifications [67]. The current specifications were introduced in November 2018 and do not contain specific regulations for PV plants.

The Flexible resource project aiming to further "...investigate the utilisation of the opportunities provided by flexible resources in as versatile a way as possible for the different usage needs of electricity transmission and distribution networks as well as customers", has been suspended in spring 2020 and research on related topics continues as part of the EU H2020 INTERRFACE project.

5.2 Reactive power provision capability

Traditional PV plants were expected to provide active power with unity power factor. However, as their penetration increases, it is needed that they support the grid by means of contributing to compensate the system reactive power losses. To that end, new grid codes request the PV plants to ensure that they can provide a certain amount of reactive power if it is requested during operation. The requested reactive power amount must be made available regardless of the plant active power point of operation and is usually agreed as a percentage of the declared nominal active power at Point of Connection (POC). This is usually achieved by increasing the number of installed converters or by adding extra equipment to the plant, such as capacitor banks, STATCOMs, or Synchronous Compensators.

5.3 Frequency and voltage stability support

In order to maintain the grid frequency and voltage stability, inverters can be equipped with frequency and voltage control algorithms. These algorithms tend to compensate frequency and voltage deviations in the grid by controlling their active and reactive power output, in a similar way to traditional generation systems.

The objective of this kind of supporting services is to enhance the robustness of the voltage and frequency of the grid in order to guarantee a stable operation of the system generators and loads.

5.4 System support during contingencies

PV inverters also should play an important role in terms of system support during contingencies. Due to the increasing penetration of PV plants in the grid, it is required that the inverters are able to stand grid events, such as faults, and provide a fast response to support the grid.

The inverters required response during contingencies can be split into two different areas:

- Remaining connected during the contingency event, in order to avoid a sudden loss of generation capability.
- Provision of fast reactive current injection in order to push the voltage to normal levels and contribute to the fault detection for the grid protections system.

5.5 Oscillations damping

In the recent years, grid operators have raised their concerns regarding the system damping as more PV generation is integrated in the grid. In order to enhance the damping of the system oscillatory modes, it is being requested that the PV plants contribute positively to damp the system oscillations by means of inclusion of Power Oscillation Damping (POD) algorithms.

5.6 Available services in the industries

Converter manufacturers have developed several control techniques in the last years in order to adapt the inverter responses to the new grid requirements and improve the grid support capabilities of the PV plants.

5.6.1 Voltage control

Voltage control can be enabled in most of the PV plants installed recently. This voltage control can be achieved in several ways, being the most used the proportional reactive power versus voltage control. This control algorithm provides a reactive power amount at POC which is proportional to the measured voltage deviation, which is calculated as the difference between a reference voltage and the measured POC voltage. If the measured voltage is lower than the voltage setpoint, the PV plant will react providing reactive power in order to push up the voltage. If an overvoltage is detected, the plant will absorb reactive power to reduce it.

Unlike the traditional proportional-integral (PI) control, the QvsV response will provide an amount of reactive power which will be proportional to the voltage error. This allows a better sharing of the reactive power contribution among near plants, and avoids unstable interaction between control loops compared to the classical PI control, and therefore it is preferrable especially if there are some other plants connected in the area.

5.6.2 Frequency control

Frequency control has been made available with the inclusion of the active power versus frequency algorithms. These algorithms tend to compensate frequency deviations in the grid by controlling the active power output, in a similar way to traditional generation systems. Similar to the voltage control, the active power variation will be proportional to the frequency deviation.

However, due to the lack of controllability of the active power output caused by the intermittent nature of the solar resources, the active power versus frequency algorithm response is limited by the PV power availability. To overcome this issue, integration of battery systems in PV plants has emerged in the recent years as a way to achieve certain level of controllability of the available output power. Hybrid solutions have been developed in order to allow the PV plants to operate ensuring a fixed power reserve or smoothing output power fluctuations caused by irradiance variations. Two different PV-BESS hybridization solutions are mainly used, at inverter level (DC coupling) or at plant level (AC coupling).

5.6.3 Low voltage ride through capabilities

In order to provide support during contingencies, converters are equipped with low voltage ride through (LVRT) algorithms. These algorithms are based on calculating a reactive current injection magnitude based of the voltage variation during the event, and provide it to the grid as fast as possible (i.e. settling time < 60 ms). Since the injected reactive current is proportional to the fault depth, a larger injection will be achieved when the faulted line is close to the PV plant as the voltage in that area will be lower. Thanks to this injection, two simultaneous objectives are achieved:

- The reactive current contribution will push the voltage levels up in order to reduce the fault depth, contributing to a more robust operation of the system.
- The extra amount of reactive current will increase the current flow towards the faulted area, therefore helping the protection system to detect the fault and correctly isolate the fault.

Apart from the reactive current contribution during the fault, the LVRT algorithms at converter level are also focused on the post-fault response. Once the fault is cleared, converters return to the pre-fault injection conditions as fast as possible in order to provide the previous active power levels so the system load flow conditions are restored. In addition, once the pre-fault conditions are restored, they guarantee a bump less transition from the converter level control which is applied during LVRT to the plant level control which is used during normal operation.

5.6.4 Power oscillation damping

One of the most recent developments that has been introduced in the PV plants is related to the plant capability to damp the system oscillatory modes. As explained in the previous section, recent grid codes request the PV plants to contribute to the system damping in order to maintain power system robustness.

To that end, converter-based plants have improved their algorithms tuning in order to ensure that they provide a positive contribution to the system damping. In addition, specific power oscillation damping controls have been implemented. Compared to a synchronous generator, the converter-based generator is much more flexible in terms of control development and the relation between the system variables can be chosen as desired. In that sense, the power system oscillation damping controls for converter-based plants can be separated into two main categories:

- POD-P: Uses the active power as the control variable in order to damp the system oscillations.
- POD-Q: Uses the reactive power as the control variable in order to damp the system oscillations.

It should be noted that, if a POD-P is used in a PV plant, its performance will be subjected to the active power availability and therefore the algorithm can be sometimes limited, similar to the frequency control explained before.

5.7 Technical advancements in the industries

5.7.1 Grid forming capabilities

Even though available services can provide support to the grid, the current inverter controls cannot maintain the system in case of grid failure. This feature has become relevant as the participation ratio of synchronous generators in relation to the total installed power is decreasing.

In order to provide these capabilities, the inverters should be controlled as voltage sources, so that they support the frequency and voltage in grid-connected mode and can create a local power grid under stand-alone mode. To deal with this, the grid-forming inverter (GFM) was originally introduced and, now, has been also proposed as a promising control mode to maintain the stability and robustness of the grid and the coming decentralized power systems formed by numerous power electronics-based microgrids interconnected. GFM inverters regulate the exchanged active and reactive powers by controlling the frequency and voltage at their output, so that they perform as voltage sources. Thanks to this, GFM inverters participate in the maintenance of the frequency and voltage, contributing to reduce the deviations when there are power imbalances.

5.7.2 Blackstart capabilities

Another desirable feature is that they present grid restoration capability or "blackstart capability", in such a way that all inverter-based DGs help re-establish the grid voltage in case of blackout. Blackstart capability is defined as the ability of a single generator or a group of them to restore the electricity supply of a grid subsystem after a blackout. When a blackout is detected, the grid area is disconnected from the main power system in which happens the failure. Then, after waiting a pre-established period of time, the generators with blackstart capability create a local voltage grid to continue feeding the nearest connected loads. Traditionally, blackstart capability has been almost exclusively offered by synchronous generators mainly due to two reasons: their performance as voltage sources and their capability of providing the high-inrush currents demanded by inductive components such as transformers or motors. This ability to restart a grid is crucial to ensure the overall system reliability. GFM inverters exhibit a promising potential since they perform as voltage sources.

5.7.3 Inertia

Another concern about PV penetration and conventional generators displacement is the inverter lack of inertia. Inertia plays an important role in power system stability because it limits and damps grid frequency variations, so the result of rotating generators displacement is a reduction in the total inertia of the power system, with the resulting increase of frequency variations. Thanks to their control flexibility, inverters can include the mechanical dynamic equations of synchronous generators in order to add an inertial component to the inverters response and increase the total system inertia, therefore mitigating the potential inertia reduction caused by the traditional plants displacement.

However, it should be noted that the converter capability to include an inertial response in the active power control is subjected to the active power reserve capability, similar to the frequency control and the POD-P control mentioned in previous sections.

5.7.4 Power reserve estimation

As it has been mentioned in previous sections, some of the currently available algorithms (frequency control and POD-P), and some of the potential control advancements, such as the inertial response, require from an extra active power availability in order to provide the desired response. In addition, voltage source operation expected from the GFM requires from a power availability in order to sustain the desired voltage waveform as load changes.

Therefore, some of the critical algorithms which are needed to support the future grid depend on the PV plants capability of managing active power production. This active power dispatchability has traditionally been one of the main drawbacks of the PV plants, so it is critical to work in advances related to active power dispatchability in order to allow the described control advancements to develop.

The most common approach to obtain a controllable active power availability is to hybridize PV plants with storage systems. However, in some cases this hybridization might not be feasible, such as for already existing plants or due to economical constraints of the projects. In those cases, it is needed to allow the plant to operate with some margin with respect the available PV power at each moment in order to ensure that some reserve is made available to be used when needed.

Operating with a power reserve implies losing active power production and therefore reducing the plant economical profit. Hence, an accurate estimation of the PV availability is required so the active power loss during normal operation is minimized while the needed amount of reserve is guaranteed. One possible way to estimate the available PV power and stablish the desired reserve is the use of weather stations in the plant which are able to measure the instantaneous irradiance. However, this approach might have some drawbacks:

- As the plant size increases, more meteorological stations are needed in order to obtain accurate measurement if the irradiance is not homogeneous along the plant.
- It is necessary to perform a conversion from available irradiance to available power, which also needs to be accurate enough and depends on other factors such as the conversion efficiency, the converters availability…
- It relies on external data rather than on the plant performance itself.

To avoid the mentioned drawbacks, another approach could be based on using the plant converters production to estimate the plant active power availability. This approach uses a certain number of converters as observers, which will be tracking the PV panels maximum power point (MPP) so their production is maximized. Their production values can be used to estimate the global active power availability across the plant and use it to provide a setpoint to the rest of the converters which ensures operating with the desired power reserve. This promising approach provides several advantages compared to the original one based on weather stations:

- The number of observers can be chosen freely without the need to add more elements to the plant, so it can be valid for both small and large plants.
- The observers can be selected among all inverters, and therefore the selected inverters (both the amount and the specific units) can be adapted in order to achieve a more accurate estimation. It is worth noting that changing from one observer inverter to another could be done without the need for any extra equipment.
- The availability estimation is directly obtained as producible active power based on converter outputs, without the need for any irradiance to power conversion, therefore increasing the estimation accuracy.

Based on that, the “observers” approach is a promising technique to estimate the plant active power availability, thanks to its flexibility. In addition, it could be combined with the data from meteorological stations to improve the accuracy of the estimation. Thanks to this active power availability estimation, the plant will be able to operate with a certain active power percentage of margin with respect the total available, ensuring that a reserve is maintained to allow the previously described controls work without limitations.

6 INTEGRATION OF PV INTO SMART GRIDS (COMMUNICATION)

6.1 Available communication technologies and protocols with PV for smart grid applications (state of the art in different countries)

Before proceeding to the state-of-the-art analysis, it is important to differentiate the involved communication routes in terms of PV integration into smart grids. Essential terms associated with the communication to PV systems are described in the table below.

Table 15: Overview of the important networks in smart grids.

Abbreviation	Description	Area of Application	In the focus of this document?
WAN	Wide Area Network	Network for the tele-communication between the centralized backend systems by utilities or system operators (utility SCADA, monitoring system) and PV systems (residential PV or local SCADA of PV plants)	X
LAN/HAN	Local Area Network/ Home Area Network	Network for the data exchange and interaction of PV systems and local systems, such as local controller, home energy managements, gateways and intelligent control units.	(X)
FAN	Field/Farm Area Network	Communication network of PV plants on the plant-level	(X)
LMN	Local Metrological Network	Network for the metering components in local areas.	-

In the following table, several commonly used communication technologies are introduced with a short description and current application level in different countries. Technical details are expounded in individual sub-sections. More details about the advantage and disadvantage of some of these technologies can be found in an IEA technical report [65] and another open-source publication [68]

Table 16: Overview of the communication technologies in smart grids.

Communication technologies	Short description	Application in different countries					
		Germany	France	Spain	Austria	Belgium	Finland
Ethernet	The Ethernet is one of the technologies for wired data networks defined by the standard IEEE 802.3 [69]. The application of Ethernet cables helps interconnect software or hardware in LAN, this allows the data exchange between end devices. A lot of industrial components and home devices are connected to the router by Ethernet cable, before they are interconnected with the Internet.	x			x		

Public switched telephone network (PSTN)	The PSTN is the aggregate of the world's circuit-switched telephone networks that are operated by national, regional, or local telephone operators. Basically, old modems before xDSL technology.		x				
Digital Subscriber Lines (DSL)	DSL refers to a suite of communication technologies that enable digital data transmissions over telephone lines that allows electric utilities to interconnect residential users with backend systems whilst avoid the additional cost of deploying their own communication infrastructure.	x					
Power Line communication (PLC)	PLC uses electrical power lines as signal carriers, which allows utility companies to use single infrastructure for both power and data transmission.	x	x		x		
Optic Fibre	Optical communication technologies have been widely used by electric utilities to build the communication backbone interconnecting substations with control centres.	x			x		
Cellular network	Public cellular networks which have a major benefit of larger coverage area. Utilities have extensively used cellular technologies, such as GSM, GPRS and EDGE, for data communications in SCADA and AMR systems.	x	x		x		
Wi-Fi	Wi-Fi, is one type of *wireless* technology, which is based on the IEEE 802.11 standard series and is mainly used by WLAN (Wireless Local Area Network) devices. As the name indicates, Wi-Fi is commonly used for local area networking of devices and Internet access, allowing nearby digital devices to exchange data by radio waves. [70]	x					
Virtual Private Network (VPN)	A virtual private network, or VPN, is an encrypted connection over the Internet from a device to a network. The encrypted connection helps ensure the security during the transmission of sensitive data and can therefore prevent unauthorized access to the device or to the transmitted data. VPN also has a wide application in the industrial field for the secured remote access of distributed smart devices or encrypted site-to-site connection.	x			x		
Fieldbus	Fieldbus refers to a series of industrial networks standardized by IEC 61784 / 61158, it is commonly used for industrial real-time distributed control that requires time-critical communication at the field level. In recent years, industrial Ethernet technologies have gained increasing application as they are more cost-effective and have better performance in comparison to fieldbus. [71]						

Serial communication	Serial communication technologies such as RS-485 can be used to transmit electrical signals effectively over long distances. The application of this technology enables the communication between devices in a fieldbus network as well as the connection between solar inverters and energy meters.	x	x		x		
Ripple control	Most distribution system operators (DSO) use ripple control systems to control specific loads, such as water heaters, washing machines, electrical heating systems or public lighting.	x					
ZigBee	This technology is based on IEEE 802.15.4 standard. It can provide short-range (up to 100 meters and up to 1.600 meters with ZigBee Pro) low-rate wireless communication for personal area networks. It supports different network topologies and applies for residential, commercial and industrial buildings automation, energy monitoring and AMR systems. [72]		x				
WiMAX	Based on IEEE 802.16 standard. It can support long-distance (up to 7–10 km) broadband (up to 100 Mbps) wireless communications, especially in rural and suburban areas. The benefits of this technology include high coverage, robustness and self-healing, wireless mesh. Its main application is found in home automation and AMR systems. [73]						
Satellite	The satellite communication is used for remote monitoring and control of electric substations and especially for the time synchronization based on global positioning system (GPS) technology.						
LoRa	LoRa (long range) is a proprietary low-power wide-area network modulation technique, which is based on spread-spectrum modulation techniques derived from chirp spread spectrum (CSS) technology. Nowadays LoRa-based devices and networks has become quite popular in the IoT world, including energy management and field communication. [74]	x					
Vendor-specific communication technologies	Some solar inverter vendors provide specific communication modules to establish communication routes particularly for their products, e.g. the WAN-communication to centralized energy portal and data interfaces to the energy market.	x					

In the following table, several commonly used communication protocols in the smart grid context are introduced with a short description and current application level in different countries. An overview of commonly used smart grids communication protocols is given in [75], more insights in to the utilization of standardized protocols in terms of DER integration in smart grids are provided in [76]. Technical details are expounded in individual sub-sections.

Table 17: Overview of the communication protocols in smart grids.

Communication protocols	Short description	Application in different countries: Germany	France	Spain	Austria	Belgium	Finland
Modbus TCP	Modbus is a serial communication protocol, which is commonly used for connecting industrial electronic devices. The protocol works at application level with a foundation on a client/server architecture, where the client requests server operations. By using a master multiplexing in gateway-based networks for gathering diverse communication interfaces, Modbus is capable of routing different system configurations with more than one master controlling the slave devices. Modbus can be deployed over several communication interfaces, such as: TCP/IP over Ethernet, Serial Transmission and Modbus Plus. [ref]	x			x		
SunSpec Modbus	SunSpec Modbus is an open communication standard that specifies common parameters and settings for monitoring and controlling Distributed Energy Resource (DER) systems. SunSpec Modbus utilizes SunSpec Information Models and is specified in IEEE™ 1547-2018, the U.S. national standard for DER. [77]	x			x		
IEC 61850	IEC 61850 is a set of standards of IEC Technical Committee 57 (TC57) for electrical substations automation systems and the integration of distribution systems. IEC 61850 provides a variety of advantages, including unified data model, standard communication structure, high interoperability, lower deployment costs, enhanced scalability and possibility for further improvements of systems automation processes. It was originally developed for electrical substations LANs, so it mostly employs TCP/IP protocol and Ethernet link as a communication medium. [78], [79]	x					
IEC 60870-5	IEC 60870-5 is one part of the IEC 60870 standard series which define systems used for SCADA telecontrol in electrical engineering and power system automation applications. This provides a communication profile for sending basic telecontrol messages between two systems, which uses permanent directly connected data circuits between the systems. The sub-part 101 and its extension 104 define signal-oriented tele-communication structure over TCP/IP, which can be used for WAN communication. [80]	x			x		
DNP3	The Distributed Network Protocol version 3.3 (DNP3, IEEE 1815) is an open standard for telecommunication designed for interaction between master stations, RTUs and other intelligent electronic devices (IEDs) in electrical utilities and						

	industrial environments. It was designed for SCADA systems to transmit considerably small data packets on serial communication or various other physical links. DNP3 is defined as one of the mandated interfaces in IEEE 1547. [81]						
IEEE 2030.5	IEEE 2030.5 (also known as Smart Energy Profile 2) is a standard for communications between the smart grid and consumers. The standard is built using Internet of Things (IoT) concepts and gives consumers a variety of means to manage their energy usage and generation, while its information model is built on IEC 61850. IEEE 2030.5 is defined as one of the mandated interfaces in IEEE 1547. [82]						
IEEE 1547	IEEE 1547 is a set of standards for the specification and test of utility electric power systems and interconnected distributed resources. It provides requirements relevant to the performance, operation, testing, safety considerations, and maintenance of the interconnection. The IEEE 1547 standard series suggests an information model mapping on IEC 61850 to reach high interoperability and specify interconnection requirements for all DER types. [83]						
Common Information Model (CIM)	The CIM is standardized within three different IEC standard series, namely IEC 61970, IEC 61968 and IEC 62325. Each of them has a different background and covers different use cases. The CIM provides both a powerful data model (domain ontology) as well as various interface specifications and technology (communication and serialization) mappings. Its acceptance in the electric utilities sector and active standardization work is high and makes it one of the most established standards worldwide in the energy domain. [84]						
OPC UA	The OPC Unified Architecture (UA), released in 2008, is a platform independent service-oriented architecture that integrates all the functionality of the individual OPC Classic specifications into one extensible framework. OPC UA provides the users with flexible application of its communication architecture, classic server-client over TCP/IP, or publisher/subscriber, or JSON over websockets. [85]						
IoT Protocols	Lots of industrial IoT protocols have advantages regarding communication performance and real-time interaction over the traditional communication protocol. Some commonly used IoT protocols in smart grids are for example AMQP, CORBA, CoAP, MQTT, DDS and Apache Kafka. [86]						
OpenADR	OpenADR is an open, highly secure, and two-way information exchange model and global Smart Grid standard, developed by the OpenADR Alliance in North America. OpenADR standardizes the message format used for Auto-Demand-Response and DER management so that						

	dynamic price and reliability signals can be exchanged in a uniform and interoperable way. [87]						
LoRaWAN	The LoRaWAN specification is a Low Power, Wide Area (LPWA) networking protocol using the LoRa physical layer. It is designed to wirelessly connect battery operated 'things' to the internet in regional, national or global networks, and targets key Internet of Things (IoT) requirements such as bi-directional communication, end-to-end security, mobility and localization services. LoRaWAN network architecture is deployed in a star-of-stars topology in which gateways relay messages between end-devices and a central network server. [88]	x					
EEBUS	EEBUS is a series of specification developed by the EEBUS Initiative e.V. in Germany. With a manufacturer-independent and standardized language, EEBUS enables the development of a future-proof, maintainable and simple device interface for smart grid applications. In the field of energy management, EEBUS enables the development of applications – from self-consumption optimization, tariff-optimized device operation through to network-beneficial behaviour. [89]	x					
RESTful web-interface (JSON)	Representational State Transfer (REST) is a software architectural style that was created to guide the design and development of the architecture for the network communication and data transfer. REST defines a set of architectural constraints that help in obtaining a uniform interface and guiding the behaviour of components. Web APIs following the REST constraints are informally regarded as RESTful. RESTful services are commonly based on HTTP methods to transmit data via URL-encoded parameters or XML/JSON format. Nowadays lots of DER system vendors also have deployed RESTful data services to enable the DER communication in HAN or WAN. [90]	x					
Other vendor-specific protocols	Besides the standard protocols mentioned above, lots of device manufacturers also implement communication interfaces using proprietary protocol or vendor-specified protocols.	x	x				

6.1.1 Germany

General Information / Background

In Germany, the grid communication to PV systems has been seen as one fundamental element of the future smart grid operation, technical committees and legislators have addressed this point in several regulatory documents.

BSI standards for the Smart-Metering-Infrastructure:

The German Federal Office for Information Security (BSI) has established the technical guideline series TR 03109 [91] in the past years to specify the certification and operation of the Smart-Meter-Gateway (SMGW), Controllable Local System (CLS) control unit and SMGW-Administration (GWA). This series is still under further development.

Legislation framework:

As mentioned in Section 4.2.1, the Metering Point Operation Act (MsbG) was established in 2016 along with the Law on Digitalisation of the Energy Transition (Gesetz zur Digitalisierung der Energiewende, GDEW) [92]. It raised the fundamental role of smart meter components and systems in the era of the Energy Transition and defined the application of SMGW as the key element of standardized, secured communication gateway.

According to the § 9 section (1) of the novel German Renewable Energies Act (EEG 2021) [93], all PV systems in Germany with an installed capacity over 25 kWp must be equipped with a technical facility to ensure that at any time, the PV system can:

- provide the actual feed-in energy
- be remote controlled by step or step less

Besides, according to the § 9 section (1a), a grid-interconnected PV system with an installed capacity between 7kWp and 25kWp, which is coupled with a controllable load, must be equipped with a technical facility to ensure that its actual feed-in energy can be retrieved at any time.

In connection with the § 30 of the MsbG, the technical facility mentioned in EEG 2021 § 9 should work together with a Smart-Meter-Gateway, which is the vital component of the TR 03109 series and is supposed to be massively rolled out in the coming years.

During the interim period till the installation of SMGW, the PV systems are regulated by the last version of the EEG (EEG 2017) [94], where the utilization of SMGW has not been specified and the remote controllability shall be fulfilled only by the installation of a technical facility, such as a ripple control receiver.

FNN recommendation for CLS control unit:

As one necessary supplementary of the Smart-Meter-Infrastructure, the role of CLS control units has been defined by the TR 03109, while there is a lack of technical specification for standardized CLS applications. One available technical guideline is the recommendation for CLS control unit given by VDE/FNN (Verband der Elektrotechnik, Elektronik und Informationstechnik - Forum Netztechnik/Netzbetrieb) [95], which suggests the utilization of the standard series IEC 61850 for WAN-communication and provides data model template for further development.

In the table below, several communication technologies applied in Germany are briefly explained, the collected information are based on the experience from the cooperation with DSOs and service providers, relevant reports and studies, as well as the information specified in the PV inverter data sheets specified by different vendors.

Table 18: Currently used communication technologies in Germany for the communication to PV systems. The table was filled by THU based on knowledge from previous projects and literature study.

Communication technologies	Areas of application	Applicability for PV data
Ethernet	LAN/HAN, FAN, WAN	Commonly used technology for WAN and HAN connection.
DSL	WAN	Commonly used WAN technology in Germany, using a DSL router allows devices in HAN to connect to the Internet.
Power Line communication (PLC)	WAN	Several SMGW vendors such as PPC AG and efr GmbH provide products with broadband-PLC (BPL) module for the WAN communication, which can be used to monitor and control PV systems.

Optic Fibre	WAN	Commonly used technology for WAN connection.
Cellular network	WAN	Some inverter vendors and data logger vendors provide LTE modems for the WAN connection to the inverter (e.g. for monitoring). Many SMGW models also have integrated cellular interface (antenna) to enable the WAN connection.
Wi-Fi	LAN/HAN	Some inverters may be equipped with a Wi-Fi interface to be integrated in the local network.
Virtual Private Network (VPN)	WAN	To enhance the security level of the Smart-Meter components, several IT-system providers (GWA, mobile service provider) allow or require the WAN-communication of SMGW to be performed with in a secured VPN.
Fieldbus	FAN	Mainly used in PV plants and commercial PV systems with large capacity and multi-inverter network
Serial communication	FAN	Mainly used in PV plants and commercial PV systems with large capacity and multi-inverter network
Ripple control	WAN	With only minor modifications a ripple control system can be used to control PV systems and thus to increase the PV hosting capacity of an electrical power system. In Germany this technology is relatively widely used to meet the technical requirements defined in EEG.
LoRa	WAN	LoRa technology is the basic for LoRaWAN applications.
Vendor-specific communication technologies	FAN, WAN	WAN-gateways provided by inverter vendor, which realize the WAN connection to the centralized cloud energy portal or market interface; or FAN plant network manager used for the interconnection of inverters within a PV plant as well as the FAN-connection to SCADA at the plant level.

Table 19: Currently used communication protocols in Germany for the communication to PV systems. The table was filled by THU based on knowledge from previous projects and literature study.

Communication protocols	Areas of application	Applicability for PV data
Modbus TCP	LAN/HAN, FAN	widely used, vendor-specific information model over Modbus TCP; Modbus interface in PV inverter integrated
SunSpec Modbus	LAN/HAN, FAN	Widely used by inverter-vendors with big market share, SunSpec interface in PV inverter integrated
EEBUS	LAN/HAN	The EEBUS specification has been deployed in the PV branch to enable the integration of PV systems in the HEMS. e.g. SMA Home Energy Manager for compatible devices [96]
RESTful web-service (JSON)	LAN/HAN	Some PV inverters have implemented RESTful interface to enable JSON-formatted data transmission, e.g. Fronius solar API [97].

IEC 61850	WAN	An individual deployment of standard telecommunication protocol is possible by mapping Modbus parameters, no common implementation by inverter vendors and data logger providers available. Direct usage of IEC 61850 for PV communication can only be seen in research projects.
IEC 60870-5	WAN	An individual deployment of standard telecommunication protocol is possible by mapping Modbus parameters, no common implementation by inverter vendors and data logger providers available.
LoRaWAN	WAN	Some inverter vendors provide users with LoRaWAN module to establish the WAN-connection to the centralized energy portal for monitoring and inverter control
Other vendor-specific protocols	WAN	Several inverter vendors have their own cloud portal.

6.1.2 France

In France the distribution network is mostly (95%) handled by Enedis. Therefore, you can find most of the documents related to network here: https://www.enedis.fr/documents.

For production sites connected with less than 36 kVA from the grid and less than 10 kVA injection, the Linky smart meter is used (PLC and then GSM transmission to the data centre).

For larger site, there are dedicated counters: SAPHIR [98], ICE-2Q/4Q [99] or PME-PMI [100] (such as this SAGEM one: [101]). They use the TRIMARAN+ protocol for transport outside the premises, and EURIDIS protocol for inside [102]. The transmission outside is done using a plain old phone line (PSTN network).

From a regulatory side you can see that a plant larger than 120 MW needs to be able to receive control orders:

https://www.legifrance.gouv.fr/jorf/id/JORFTEXT000042032189/

6.1.3 Spain

In the Article 7 of the Royal Decree 413/2014 which regulates the electric energy production from renewable energy resources, [12], the monitorization and controllability requirements for generation, demand and storage are specified:

- Facilities with installed capacity > 5 MW (or lower installed capacity but aggregated by same technology being the total size greater than 5 MW) must be attached to a control centre, which will act as an interlocutor with the system operator.
- Facilities with installed capacity > 1 MW (or lower installed capacity but aggregated by same technology being the total size greater than 1 MW) must send telemetries to the system operator, in real time, individually in the first case or aggregated in the second. These telemetries will be sent by the facility owners or by their representatives and may be sent through the control centres of the distribution company, when agreed between both parties. The distribution system operators will have access to telemetries of those installations connected to their networks in real time.

Moreover, every installation participating in the balancing services markets, must be attached to a control centre and, therefore, send telemetries [103].

The Spanish System Operator, REE, has participated in the development of a consumption visualization platform for self-consumption installations <1MW. Such a platform receives information in real time from the platforms of the inverter manufacturers, covering the lack of information derived from the current regulation, which does not contemplate the reception of information in time of the power generated for installations of less than 1 MW, nor the measurement of the energy produced through the meter [26].

6.1.4 Austria

Data exchange production site:

In Austria the distribution grid is handled by 122 DSO, which operate around 260,000 km of grid at several grid levels of the distribution grid. For grid introduction of new production sites the "Technische und organisatorische Regeln für Betreiber und Benutzer von Netzen - TOR Erzeuger" bundle many provisions for power generation plan: [104], [105]

Table 20: Telecontrol and data exchange according to "TOR Erzeuger".

TOR	power	telecontrol	standard
Typ A	< 250 kW	Termination of the Active power output (1 potential-free contact)	
Typ B	≥ 250 kW - < 1 MW	gradual reduction of the active power output (4 potential-free contacts)	
	≥ 1 MW – 35 MW	Setpoint specifications and real-time data	Communication standard: e.g. IEC 60870-5-101 or IEC 60870-5-104
Typ C	≥ 35 MW – 50 MW		
Typ D	≥ 50 MW		

Data exchange customer site:

Smart meters are electronic electricity meters that can electronically measure and store energy consumption. This gives consumers the opportunity to track their electricity consumption in order to identify electricity-saving opportunities or take advantage of future flexible energy prices.

The smart meter offers a wealth of useful additional functions that go far beyond simply recording electricity consumption, such as:

- Two-way communication (bidirectional communication)
- Acquisition of short measurement intervals (e.g. 15-minute values)
- Acquisition and storage of metered values
- Multi-tariff functionality
- Import and export measurement
- Remote release of power consumption as well as power limitation
- Communication interfaces for external applications (additional meters, household appliances, etc.)

As an example, the DSO of the Austrian's demo site usually uses Landis + Gyr E450 for metering the prosumers. This Smart Meter transmits the consumed energy via PLC to the DSO for the metering. For external application a user interface (open HAN interface) optical, as well as M-Bus wired is provided. [106]

6.1.5 Belgium

In Belgium, the roll out of smart meters is ongoing (Section 4.5.2) on the level of households and the low voltage grid. Monitoring of solar PV installed on this level of the grid, is done via the smart digital meters. The communication is done via GPRS using the protocol NB-IoT (LPWAN) in Brussels, Wallonia and Flanders (4G LTE cat NB1) [63] [107] [108].

For medium to larger production installations already existing technical specifications were in place for monitoring and remote control (telecontrol).

Monitoring of production installation with a total installed capacity of more than 100kVA was done via AMRs (Automated meter readings) in Flanders (>100kVA), Wallonia (>100kVA) and Brussels (>56KVA on LV and all on HV) [109] [110] [111]. Communication of (new) AMR meters is done via GPRS.

Remote control, as mentioned in the appendix of the Connection Contract for electricity provided by Fluvius, “Modulation of production installation on command of the distribution grid operator” is applicable to systems with a total installed apparent power of 1.000kVA behind the same grid connection. Modulation is done via a Remote Control Box installed by the DSO. The technical specifications for electricity production installations [112] mention two communication possibilities: CAB (Central Remote Control) with frequencies 110 Hz - 1500 Hz and PLC (Power Line Communication) with frequencies 3 kHz – 95 kHz. The document [113] reports communication via GPRS/LTE. The Remote Control Box can be used to curtail (shut down or modulate) the production installations in case of congestion. Communications protocols reported by [113] and [112] are IEC 61850 and IEC 60870-5-104.

6.1.6 Finland

General Information / Background

Starting from February 2022, Finland intends to start using a centralised information exchange system – **Datahub** – for the electricity retail market.

“The system is intended to speed up information exchange between parties, with the data being available to everyone entitled to it at the same time – in an impartial and up-to-date manner.” – Fingrid [114]

The Datahub enables distributed energy communities which allows to utilise the electricity generated at a more suitable place (south) in a residence not necessarily located in the vicinity of the production site [64].

6.1.7 Summary

Based on the information provided by the project partners, different communication technologies and communication protocols are being used in different countries, the application of them vary significantly depending on the size of PV systems, the interconnected voltage level, the role of data user and the purpose of the data usage.

A lot of utilities still rely on the data provided by smart meters for the system operation, especially for small-sized and medium-sized PV systems. This indicates a lack of usage of data provided by PV system itself, much valuable information has not been utilized in an efficient, stable and secured way. One possible reason is the insufficient infrastructure for communication routes and data interfaces; another cause is the relative low interoperability level of PV communication, even the protocol SunSpec, which is explicitly designed for PV system, is not in a widely use by utilities and other market participants; besides, the bandwidth and stability of the communication routes may also affect the data quality when large amounts of data are transmitted, which restricts the data volume.

When talking about communication, the interfaces and infrastructure on both sides (field systems in HAN and backend systems in WAN) must be considered. It can be clearly seen in the last decade, that the PV system/service providers and utilities are sticked to protocols to which they are most familiar, because the rollout of new communication devices and the implementation and deployment of new data interfaces are quite cost-intensive. This situation points out the necessity of using standardized protocols that can be well understood by both sides, or the implementation of a unified process of protocol conversion to harmonize similar parameters in different protocols.

6.2 New developments in the communication with PV

6.2.1 Germany

In Germany, there are plenty of research projects and industrial initiatives dealing with the digitalization of the energy transition, including the concept of Smart-Meter-Infrastructure and Controllable Local System. New developments in the communication to PV systems open the door for advanced application of PV data and intelligent functionalities, such as real-time monitoring and control of PV by utilities, which may contribute to the grid stability and enable the high utilization of grid hosting capacity. These will indirectly stimulate the growth of PV on different voltage levels.

Recent research projects and studies in Germany related to PV communication as well as ancillary services based on the communication are listed in the tables below.

Table 21: overview of studies related to PV communication in the past 5 years.

Studies	Year	Investigations related to the topic	Main findings/objectives
dena analysis [115]	2018	Communication interfaces und standards for the digitalization of the energy transition.	This report provides an overview of the status quo to give market players a structured introduction to this complex subject. At the same time, it identifies open fields and derives needs for action. In the report, various aspects of digitization in the energy system were examined and the standard IEC 61850 has been proved to be a core communication standard in future smart grids.
Ernst & Young –study [116]	2021	Barometer Digitalization of the Energy Transition: Modernization and progress barometer for the evaluation of the grid-based energy industry digitization process. Progress and limitations of the Smart-Meter-Rollout.	There are structural challenges both for scaling the rollout numbers and for new business models, such as uncertainties regarding technological and regulatory risks, lack of scaling of smart metering systems, or low active consumer demand. The level of information on the rollout and awareness of electronic meters is still low among the general public and industry. Overall, however, the rollout of Smart-Meters-Infrastructure is increasingly accepted and supported.
IEA-Task 14 Report [65]	2020	Communication and Control for High PV Penetration under Smart Grid Environment	The integration of DERs, such as solar PV system in distribution system or customer premises has motivated the development of different control strategies to take advantage of distributed and controllable resources. The increasing penetration of distributed PV systems also request for a grid-scale coordinated control network. The large-scale deployment of sensing, two-way high-speed communication infrastructure and the advanced PV inverters have provided the platform to realize the distributed, real-time closed-loop control

			architecture in the near future. The communication technology selection and implementation significantly affected by geographical, administrative, physical and logical reasons.
IEA-Task 14 Report [117]	2021	PV as an ancillary service provider	This report aims to highlight the status and the potential of PV and PV hybrids as ancillary service providers. It provides a collection of laboratory and field experiences from different IEA PVPS countries and for different ancillary services. Regarding different aspects of ancillary services, it highlights the findings of the different international experiences and provides an outlook on PV systems and PV hybrids as an ancillary service provider.

Table 22: overview of research projects related to PV communication in the past 5 years.

research projects	Project duration	Investigations related to the topic	Main findings/objectives
CLS-APP BW [118]	2016-2018	Utilization of standardized data model and communication protocol for DER-grid communication.	This project proved that utilization of CLS control boxes is suitable for the operation of smart grids, based on international standards. Existing components of the prosumer are integrated into the network in order to achieve improved feed-in management, adaptation and control of system services and secure market integration.
ESOSEG [119]	2015-2018	Development of a DSO service/data platform and data adapters based on the utilization of Common Information Model (CIM).	Within ESOSEG, an open-source framework for simulation and optimization has been developed based on CIM standards. It successfully demonstrated a CIM-based data platform for environmental compatibility, economic efficiency and resource efficiency of electricity grids and the security of electricity supply in Germany.
Grid-Predict [120]	2015-2018	Coordination of PV and battery system and development of methods to correctly determine the grid condition even at high levels of fluctuating feed-in at the low-voltage level.	This project successfully demonstrated the monitoring and control of PV and battery system using standard protocol IEC 61850 and tele-communication routes to the SCADA system; a computation-optimized probabilistic load flow method was developed to achieve predictive grid calculation.
SINTEG-C/sells [121]	2017-2021	Demonstration of the Smart-Meter-Infrastructure, secured DER control with CLS-gateways and market interface for flexibility.	Setup of a complex Smart-Meter-Infrastructure including CLS-management system; concept for the system integration of smart grid components; Development of a partial-automated framework for the deployment of Smart-Meter-components; simulation framework for DSO-TSO coordination and real-

			time simulation of distribution grids; secured DER remote control with IEC 61850 through the encrypted channel established by SMGW; Integration of consumer and prosumer energy system in DSO SCADA.
Smart beats Copper, EU ERIGRID [122]	2017-2018	Tele-communication and control of PV inverter in distribution grid SCADA; Power-Hardware-in-the-Loop simulation of PV inverter control.	A network simulation configuration combining the concepts of hardware and software in the loop (HIL-SIL) has been developed and validated for laboratory applications. The real-time control of a PV inverter by the logics in the SCADA system has been demonstrated.
SYS/DL2.0 [123]	2014-2018	Developing and validating the system-based principles for the coordinated provision of ancillary-service upstream products; Infrastructure for the standardized data exchange.	A platform was developed to enable distribution grid operators to provide the reactive power required for the stable and secure operation of electrical grids by coordinating the control of decentralized generation plants. In addition to control and optimization modules, the platform also includes the necessary components for standardized communication between distribution grid operators and transmission grid operators.
PV-Regel [124]	2020-2022	Potential of using decentralized PV systems to provide system balancing power.	Utilization of Smart-Meter-Infrastructure and standardized IEC 61850 data model; Deployment of communication protocol such as MQTT with higher reliability to achieve better system performance.
Connect+ [125]	Implementation project of the Redispatch 2.0 Scheme by BDEW	Connect+ aims to ensure data exchange for the implementation of Redispatch 2.0 in accordance with the legal requirements of the NABEG by 01.10.2021.	Specifications for DSO; setup of unified IT-platform; new concept, use cases and working process to bind PV-systems to the Redispatch 2.0 schema in Germany.

6.2.2 France

“French solutions for smart grids”, is a French dedicated portal for innovation around smart grids. [126] is prospective document for 2030 objectives with improvement areas.

Examples of improvement areas related communication / smart meters:

- *local and collaborative system that meets the new expectations of customers:*

  “Smart meters offer end customers a better understanding of their energy consumption and of the origin of the energy consumed, paving the way for more "intelligent" energy management. At the same time, consumers are encouraged to deploy their own means of production (photovoltaic, biomass, etc.) or storage, and to develop new uses, such as electric vehicles and intelligent charging stations. Thus, the "prosumer" can make new trade-offs on his equipment, which he controls individually or collectively, within "energy communities", and act directly on the energy system, in particular through demand response and self-consumption."

- *a resilient system*:

  "At the operational level, the deployment of new communication standards for Smart Grids (redundancy, G3 PLC, 5G, multi-channel, IEC61850...) as well as the improvement of telecontrol hardware components (MIL STD) appear to be priority projects, in order to improve the management of local resources, whether in terms of energy production, consumption or storage."

There you can also find few projects to improve the smart grid in the next years:

- IssyGrid: "IssyGrid is a demo-project led by Enedis and some 10 industrial partners for a large range of smart grid use-cases that have been scaled up to a whole urban district: flexibility, storage, integration of local solar power, smart EV charging, smart lighting, as well as applications for power consumption optimisation in households and office buildings." https://www.thinksmartgrids.fr/en/issygrid-enedis-pilot-project
- Nice Smart Valley: "Nice Smart Valley is part of the European project Interflex, in the framework of the Horizon 2020 program, involving 20 partners across Europe to experiment with new forms of flexibility. In France, the project tests smart grids solutions in order to integrate renewable energy sources and electric vehicle charging stations into the grid. Experiments include collective self-consumption with storage systems in a residential district, the complementarity of the gas and electric grid, and temporary islanding on the scale of a neighborhood. Finally, the project provides the Nice Côte d'Azur metropolis with a wide variety of data concerning the electricity distribution grid and the flexibilities enabling to control its energy consumption and make savings."

6.2.3 Austria

Against the background Austrian's goals in reduction CO2 emissions, increasing integration of renewable energy production, including increasing PV power, intelligent grid solutions are considered key to the development of energy supply towards sustainability.

To ensure a reliable grid operation with a high penetration of renewable energy production an update process at DSO side is started, implementing the guidelines according to the "TOR Erzeuger" directive into their systems. [127]

The new challenges facing DSO's:

- Integration of volatile distributed generation
- Change of grid usage (load pattern) by "flexible" grid users
- Redispatch in distribution networks as a means of removing congestion.
- Coordinated system and network management (operational cascade TSO DSO)
- Coordinated voltage and reactive power management (TSO DSO)
- Generation and load flow forecasts as a building block of operational planning
- Integration of flexibility providers in redispatch and market processes

For implementation of a reliable data exchange, real-time monitoring, and controllability of renewable energy production the "TOR Erzeuger" directive invokes the IEC 60870-5-101 and IEC 60870-5-104 standard for communication with SCADA systems. For PV system, where inverters mostly provide Modbus TCP as a communication and control interface, an additional gateway which allows a remote control according to the requirements of the SCADA system.

6.2.4 Finland

Datahub 2.0 promises to improve measuring from hourly resolution to 15-minute resolution in metering and balance settlement, alongside a new **accounting point energy metering.** The Datahub 2.0 is expected to come online in 2023, according to Fingrid [128].

Accounting point energy netting “refers to the netting of measurement data from related consumption and (small-scale) production accounting points within a 15-min time step”.

Fingrid has chosen Nokia to install an IP/MPLS network to enable smart grid capabilities for the national power grid [129].

6.3 Gap analysis

As pointed in the section 6.1.7, to enable the robust communication to PV systems, a common understanding of the information and communication level should be achieved between PV system/service providers and utilities. During this process, a universal application of essential information objects is vital, and both existing communication infrastructure and new technologies should be considered.

The SERENDI-PV partners will work together to improve and demonstrate the utilization of standard protocols/data models that have a quite good DER conformality, e.g. SunSpec and IEC 61850. It will be proved that choosing a proper standardized protocol and the associated data models could facilitate the implementation of high-level business use cases at the function layer, reduce the engineering complexity and enhance the communication stability.

7 RELIABLE PROVISION OF ANCILLARY SERVICES BY SOLAR-PV SYSTEMS

The term “ancillary services” refers to a large range of services delivered by grid connected assets to grid operators, in order to support the safe operation of electrical grids. Provision of ancillary services, and especially its subset of balancing power, with solar-PV is still in its infancy. We start this chapter with a short overview of the two main groups of ancillary services: those outlined in the **grid connection** requirements and those related to **system balancing**.

In the following section, we focus on the sources of uncertainty for solar park operators or other market parties that wish to use solar-PV for the provision of balancing power. These sources of uncertainty make it either impossible, unprofitable, uncompetitive, or at least very risky to provide balancing power with solar-PV. Consecutively, several solutions are discussed that could help close the gap to competitive and profitable provision – both from a technical, operational, and market design perspective. It is followed by an overview of past and current research projects piloting the use of solar-PV in ancillary services. Finally, an overview is provided on how the SERENDI-PV project aims to contribute to these solutions.

7.1 Participation of solar-PV in European ancillary services

In work package WP1 of the SERENDI-PV project, task T1.1.2 assessed the regulatory environment for the integration of solar-PV in European electricity grids. It was shown that the term “ancillary services” refers to a large range of services delivered by grid connected assets to grid operators, either obligatory or voluntary with **market-based remunerations** (see D1.2). The aim of these services is to ensure that assets can be integrated into electrical grids without endangering safe and reliable system operations, and possibly actively contribute to resolving frequency, voltage, congestion, or blackout situations. These ancillary services can roughly be divided in two groups:

- Ancillary services specified in the **grid connection requirements** for generators:
    - Grid connection requirements stipulate the necessary technical capabilities of a power generation asset to be allowed to connect to the public grid.
    - They mostly dictate the required behaviour in the case of exceptional situations in the grid, such as large frequency or voltage deviations. But they also include services like voltage control and reactive power provision, and sometimes redispatch. They also address the required behaviour of generation assets in case of blackouts.
    - These services differentiate between synchronous generators (so-called Synchronous Power Generating Modules or SPGMs) and renewable power generating assets (so-called Power Park Modules or PPMs). The grid connection requirements consider the state-of-the-art technical capabilities of solar and wind parks.
    - Ancillary services specified in the grid connection requirements are usually not remunerated. When they are, the remuneration is usually regulated and not market based.
- Ancillary services for providing **balancing power**:
    - This subset of ancillary services is especially important in the day-to-day operation of the grid. Balancing power is used by grid operators to maintain a stable frequency and restore imbalances in their control area.
    - In the liberalized European energy system, grid operators are obliged to procure these services from market parties. Provision of balancing power can have a big impact on the operation of the asset and therefore presents significant operational efforts, and (opportunity) costs.

- As a result, provision of balancing services is usually remunerated. Most EU member states work with auctions to ensure a market-based remuneration where the cheapest providers are selected to provide the service.
- As shown in D1.2, there is no evidence of EU member states that explicitly forbid solar-PV to participate in balancing power auctions, but market design and technical requirements often hinder solar-PV from participating in practice (see D1.2). Provision of balancing power by solar-PV is therefore in its infancy in Europe.

Per definition, operational solar-PV parks can provide the ancillary services outlined in the grid connection requirements – otherwise they would not have been granted access to the public grid in the first place. Participation to these services is binary: either the solar-PV plant can prove compliance, or it can't. Compliance is usually a matter of selecting certified inverters with built-in fault response capabilities, and/or the installation of a remote-control unit that complies with the specifications of the relevant grid operator.

Participation in balancing power, on the other hand, is less straightforward. Per definition, balancing power or reserve power is procured in advance by grid operators[1]. This way, they ensure themselves of sufficient means for balancing in case of large system imbalances. As a result, renewables like solar-PV need to rely on forecasts to determine how much reserve power they can offer in an auction. The response time, duration of provision, ramp speed, and monitoring requirements as stipulated by the relevant grid operator need to be always respected. Since such requirements are not (necessarily) part of the grid connection requirements, solar parks are usually not yet adequately equipped for the provision of balancing power during their initial construction.

7.2 Sources of uncertainty in offering balancing power with solar-PV

Providing balancing power is not a 'best effort' endeavour. Grid operators expect reserve power contracted in its auctions to be available and to respond according to the technical requirements. Failure to provide correctly has two major implications:

- **Endangering safe system operations**: Since balancing power is used by Transmission System Operators (TSOs) to maintain a stable and safe system and avoid unwanted power flows over interconnectors with neighbouring control areas, failure to provide balancing power directly endangers safe system operation. When the response by one provider is not sufficient, a grid operator will activate other selected providers until the contracted means are exhausted. If at that point the system frequency or control area imbalance is not restored, safe grid operation is compromised.
- **Financial penalties and exclusion of the service**: When a balancing service is not provided adequately, grid operators in several EU member states will penalize the failing provider. Repeated failures will often lead to exclusion from offering the service in the future.

There are several sources of uncertainty for market parties that wish to provide balancing power with a solar-PV park. An overview of the most important ones is given below:

[1] Some EU Member States have introduced the possibility to offer balancing power on short notice. This is known as 'free bids'. Market parties can offer their flexibility without a commitment days or weeks in advance. This enlarges the pool of assets that can be activated by the grid operators in times of need, but cannot replace the need to procure balancing power in advance.

- **Technical sources of uncertainty**: Is the solar-PV park equipped appropriately and technically able to fulfil the response requirements of the relevant grid operator? Different technical aspects need to be considered:
  - Response time: services like FCR (Frequency Containment Reserve) require a response in a matter of seconds. That means that the generation, transmission, and processing of the power setpoint need to happen with minimal delay.
  - Response accuracy: some grid operators require a response with kilowatt precision. Other grid operators define an accuracy band around the demanded setpoint. The inverter needs to regulate the power output with sufficient accuracy.
  - Real-time communication provision: most grid operators require real-time reporting of the response in products like FCR and aFRR (automated Frequency Restoration Reserve). If the communication channel is interrupted, provision of the service is usually assumed to have failed too.
- **Resource related sources of uncertainty**: An obvious source of uncertainty is the lack of upfront knowledge about the exact power output of a solar-PV installation at a future point in time. Since reserve power needs to be committed in an auction that takes place hours, days, or weeks in advance, for delivery in a specified time span, this uncertainty creates a double risk:
  - The longer in advance the reserve power need to be committed in the auction, the higher the risk that final solar production is significantly different from the forecast used to inform bidding in the auction. The risk is that either too much has been sold, or too little. In the first case, the market party won't be able to meet its reserve power commitment, in the latter additional revenues have been foregone.
  - The longer the delivery time spans, the higher the risk that the lowest power production over the time block (which determines the amount of downward balancing power that can be committed in the auction) was wrongly forecasted.
- **Market related sources of uncertainty**: Market design and ancillary service market dynamics can also form a large source of uncertainty. The following aspects need to be considered:
  - Most grid operators use a baseline or reference to determine how much balancing energy is effectively provided to the grid by an asset. The baseline represents the power output of the asset if modulation of the power output would not have taken place. Different grid operators use different baselines, but usually they aim to use one baseline approach for all participating market parties and technologies. That means the baseline might (at times) poorly reflect the would-be power production of the solar park. The lack of a baseline that properly represents solar-PV is a source of uncertainty.
  - Some grid operators allow providers of reserve power to buy or sell committed volumes among one another in a secondary market. This allows market parties to manage their commitments in case of outages, changing operational schedules, forecast updates etc. For solar-PV operators, this offers an opportunity to limit the impact of forecast errors on committed volumes in the auction. Yet, it remains uncertain if other market parties will be available in the secondary market when needed, and if they are willing to offer a secondary market deal at a reasonable price. Especially in moments of large, unexpected weather changes, it is likely that most solar parks will be looking for an exchange on the secondary market at the same time.
  - Market designs change over time. There is uncertainty that compliance with the requirements today guarantees compliance in the future. Investment in equipment for remote control and monitoring can hence become stranded.

- o Ancillary services procured via auctions get a market-based remuneration. That remuneration hence depends on supply and demand dynamics and will change over time. This is a large source of uncertainty for all participants in ancillary service auctions, but it is not unique to solar-PV.

7.3 Possible solutions to sources of uncertainty

In the previous section, we looked at the three main areas of uncertainty in providing balancing power with solar-PV. In this section, we aim to list several possible solutions to mitigate these sources of uncertainty.

7.3.1 Solutions to technical uncertainty

Technical uncertainty revolves around the question whether a solar-PV park is sufficiently equipped and technically able to fulfil the technical requirements of the relevant grid operator. The main solutions are:

- The development and installation of dedicated (remote) control equipment and data loggers. Sufficient testing is paramount to ensure compliance with the technical requirements before participating in an auction. Operators of solar-PV parks can work together with third parties like aggregators like project partner Next Kraftwerke, who often develop dedicated hardware and software to comply with the technical requirements of grid operators.
- Since provision of ancillary services with solar-PV is still in its infancy in most of Europe, it is rather the exception than the norm to include dedicated equipment during the initial conception of a solar-PV park. This means the park needs to be retrofitted at a later point in time. Potential compatibility issues and extra site visits drive up the complexity and costs of such intervention. The obvious solution is hence to consider provision of balancing power during the origination of the solar park and include the necessary equipment from the get-go. To ensure interoperability, standardization of inverter interfaces through communication standards like IEC 60870, IEC 61850 or IEC 61970 is a must.
- Uncertainty around the potential failure of communication channels can be addressed by implementing a redundant communication system.

7.3.2 Solutions to resource related uncertainty

Resource related uncertainty revolves around the lack of upfront knowledge about the exact power output of a solar park at the time of the auction of the ancillary service. The main solutions are:

- An evident solution is to improve the forecasting capabilities for solar-PV. A special focus should go to reducing uncertainty around the minimal power output over the considered time span, since this often informs the amount of flexibility that can be committed in the auction.
- A reduction in the duration of ancillary service product horizons and the delay between the ancillary service auction and its delivery would significantly decrease the impact of forecasting uncertainty on the reliability of provision by solar-PV.
- Market parties that want to provide ancillary services should aim to leverage the reduction of forecasting uncertainty through portfolio effects. By offering balancing power with a pool of solar-PV assets over a larger geographical area, local weather deviations will partially cancel each other out on the portfolio level – increasing the reliability of committing power in the auctions.

- To further reduce uncertainty, the portfolio can be expanded beyond solar-PV technology. In fact, most market parties participating in balancing power already use a hybrid pool. Different renewables can be complemented with e.g. energy storage and demand response sites.

7.3.3 Solutions to market related uncertainty

Market related uncertainty revolves around aspects of market design, market dynamics, and the changes thereof. They can be addressed as follows:

- Uncertainty created for solar-PV by a 'one-size-fits-all' baseline approach can, evidently, be solved by adopting a dedicated baseline methodology that considers the intrinsic characteristics of solar-PV. Ideally, such baseline uses site specific or local weather data to calculate the would-be power output of the solar park during moments of balancing power provision.
- Uncertainty around the ability to find solutions in case of over- or underselling of balancing power can be addressed by closing (long-term) deals with other market parties with firm assets that can absorb a shortage or excess of balancing power. This would give the right to the solar park owner to demand taking over part of the balancing commitments on short notice. Such bilateral options contracts will come at a price, reflecting the opportunity cost of keeping the firm asset available instead of using it in the market.
- It is natural that market designs change over time and uncertainty around market design applies to all participating technologies, not just solar-PV. Nonetheless, grid operators should employ business impact studies of proposed design changes and work with reasonable transition periods in case of significant changes. Market parties can mitigate the risk of regulatory changes in one grid services, by making sure they can participate in different ones. Project partner Next Kraftwerke, for example, developed its remote-control steering box to be ready for the provision of different ancillary service types.

7.4 Overview of research projects

In this section, we provide a short overview of past and ongoing research projects that investigate and pilot the feasibility of ancillary service provision by solar-PV. They are listed in the table below.

Research/Pilot Project	Project duration	Member State	Main goals and findings of the project
Baseline methodology assessment by Belgian TSO Elia	2021	Belgium	Belgian grid operator Elia conducted a study in 2021 on its baseline methodologies for several balancing products, in which the authors were involved. They also looked at baselines for solar PV. They found that using either real-time measurement from irradiance sensors or real-time power output from reference inverters could result in a baseline with more than 90% accuracy.[130]
Pilot project balancing with renewables by Danish TSO Energinet	2019 - present	Denmark	Danish TSO launched a pilot project at the end of 2019 to investigate balancing with renewables. The first results of delivering mFRR with wind energy were published and look promising. Tests with solar PV are underway. [131]
Research project into provision of secondary	Unknown	Germany	Fraunhofer IEE investigated the possibilities to provide secondary and tertiary balancing power in

and tertiary reserve with solar-PV by Fraunhofer IEE			Germany with solar PV and wind power. They found that, if a dedicated probabilistic forecasting model is used while pooling different parks together, solar PV and wind are technically able to provide these services. [132]
Research project into PV reactive power control for voltage support at the Transmission Distribution interface by Fraunhofer IEE	Unknown	Germany	Fraunhofer IEE investigated the possibility to provide reactive power to resolve voltage problems at the interface between distribution and transmission grid, by remotely controlling the inverters of PV plants. The field test was successful, providing 40 MVar with 6 plants. [132]
Field test by SMA to test the ability to run the Island with a hybrid PV and storage system	Unknown	Sint Eustatius (Dutch Caribbean)	The extensive field test carried out on the Island grid of Sint Eustatius has shown that a PV and storage system are able to have full grid forming capabilities, can maintain voltage and frequency at stable levels, provide uninterrupted power supply, and are able to provide fault-ride through capabilities, in the absence of synchronous power generation. [133]

7.5 Gap analysis

In this chapter, we have discussed different sources of uncertainty for solar park operators or other market parties that wish to use solar-PV for the provision of balancing power. They make it either impossible, unprofitable, uncompetitive, or simply very risky to provide balancing power with solar-PV. That is why provision of ancillary services by solar-PV is still very rare in European Member States. We listed a number of possible solutions to overcome these uncertainty gaps, which allow to reduce the risk for ancillary services provision by solar-PV. In this last section, we give a short overview of how the SERENDI-PV project is contributing to some of these solutions.

Source of uncertainty or gap	Proposed solution	Related SERENDI-PV WP or Demonstration
Uncertainty around technical capability of solar assets to provide specific services.	Validate and test technical capabilities of solar-PV for common ancillary services through pilots.	WP8 (demo assets of partners QPV, THU, NKW)
Lack of inclusion of dedicated equipment during the conception of the solar park.	Reduce risk investment in equipment through the assessment of different business cases in ancillary service provision.	WP6
Uncertainty around reliability of data transmission.	Monitor and test uptime through pilots.	WP8 (demo assets of partners QPV, THU, NKW)
Forecast uncertainty at moment of ancillary service's auction.	Quantify impact of forecast errors on reliability of service provision through simulations.	WP5 and WP6

Uncertainty around risk reduction as result of (hybrid) portfolio effects.	Quantify impact on reliability of service provision through simulations and pilots.	WP6 and WP8
Uncertainty around baseline applicability.	Propose and test dedicated baseline methodology with a European TSO.	WP8 (demo assets of partner NKW)

8 FROM FEED-IN ONLY PV TO DISPATCHABLE PV (CELLULARITY)

8.1 How to operate and coordinate the high number of PV considering the support of the grid

The PV penetration in many countries is continuously growing and PV is becoming a major energy source in the future electricity grid worldwide. Therefore, PV systems and PV hybrids need to take over more and more system responsibility by providing ancillary services such as frequency control, inertia, operating reserve, voltage or reactive power control, and black-start capability. These services can be provided by grid users, such as conventional power plants, renewable energy sources (RES), storage units, or flexible loads, to support or ensure a secure and reliable power system operation. The specifications, types, needs, and procurement procedures of these ancillary services can vary in different power systems and are changing with the progress of the energy transition in many countries.

Over the last years and decades, PV inverters have achieved a significant development driven by new and enhanced requirements for generators in various countries. PV systems have developed from passive grid users, which solely feed-in maximum active power and immediately disconnect in case of a grid disturbance, to active grid users, which can provide various grid support functions under normal and disturbed grid operation.

Nowadays, PV systems can already provide a wide range of grid support functionalities, which are increasingly applied in national grid codes worldwide. These grid support functionalities are, for example, voltage and frequency ride-trough, active and reactive power control, voltage and frequency control, and dynamic grid support.

The following points describe the different ancillary services provided by PV systems and PV hybrids that can support the grid:

- The **frequency control** is implemented in different stages, distinguished by different response times and durations, typically primary control, secondary control, and tertiary control. The provision of secondary control reserve and minute reserve using pools of Wind and PV power plants is generally possible and practicable but depends in detail on the formulation of the accuracy requirements for frequency control reserve markets by the TSOs.
- PV **power curtailment** can be an effective measure to increase the PV grid hosting capacity and can support congestion management, voltage control, and power balancing at the transmission and distribution level. Furthermore, curtailed PV may also be a source of operating reserve to manage unexpected changes in net demand.
- Local **reactive power control**, such as volt-var control, is increasingly applied for PV inverters in several countries in field applications. The local reactive power control by PV inverters can increase the PV grid hosting capacity.
- The use of grid-forming inverters that have a control approach with the capability to control the terminal voltage directly and to form the grid voltage purely by inverters under consideration of necessary reserve and storage capacity. With the increased penetration of inverter-based generators in electric power systems worldwide, the need for PV hybrids with grid-forming capabilities will also emerge in large, interconnected power systems.
- The admissible harmonic current emissions of a PV plant are often an important limiting factor within the grid code compliance assessment procedure requested before grid connection. To overcome this issue, traditionally one can either choose a “stronger” point of coupling with the public network or by adding harmonic filters of the appropriate orders to the PV system. A good alternative to both measures is a detailed analysis of the PV plant design concerning harmonic emission. Harmonic current superposition within PV plants with multiple (identical) inverters may contribute to a

minimization of the total harmonic current at the point of coupling, depending on PV plant design with harmonic order and operating point(s) of the different inverter.

8.2 Improvements that can be achieved in a cellular operation

How the energy transition and the expansion of renewable energies can be efficiently implemented in the grid has been demonstrated on a large scale in several countries, showing what the energy system of the future will look like: cellular, participatory and diverse. One example is the joint demonstration project “SINTEG C/sells” in Germany [134].

In such a cellular future energy system, cells should be understood as an additional organizational level in which decentralized energy systems such as generators, storage facilities and consumers come together as systems within the system. They thus complement the already existing top-down structures of control zones and distribution grids as bottom-up structures.

Cells can be individual buildings, but also entire properties, areas, quarters, cities or regions. A cell is characterized by the fact that it is largely autonomous in deciding on the use of the energy generators and consumers available in it.

The cell can optimally coordinate its generation and consumption. According to this approach, however, coordination can also take place between cells, and the entire energy system is thus optimized in the network.

Cells enable the active - and for the energy turnaround absolutely necessary - inclusion of those decentralized actors who so far neither participate directly in markets nor can be influenced by the grid operators.

Cells can perform the following functions:

- They can provide energy and flexibility for their own needs within the cell. Depending on the efficiency of the flexibility option, they can increase energy efficiency through short transport distances and increase resilience in the event of a crisis.
- They can flexibly provide energy for market, system and grid serving purposes. Thus, cells remain "team players" in the energy system.
- They can aggregate data for higher levels and thus reduce complexity through data sparseness. Only through this data aggregation does coordinated coordination become possible.
- In addition to balancing generation and consumption within the cell, regional energy products can also be traded between cells. In this way, consumers can directly benefit from the use of local generation plants.
- At the same time, individual cells can be operated in island mode, thus securing another system-relevant service.

The implementation of the energy turnaround is not just a technical project, but also concerns the question of how we want to organize our economy and society. The task, therefore, is to develop an energy system with which we can specifically enable the coordination of the many decentralized generation and storage facilities as well as consumers at the technical level and develop the coordination instruments in such a way that grid stability is maintained.

In perspective, it will be increasingly important to create design and participation opportunities for individuals, properties and communities as well as companies on a socio-ecological level and to ensure an attractive and equitable incentive structure.

The basic instruments resulting from the cellular approach, such as a voting cascade, regionalized markets or autonomous cells, show: There are viable and economical solutions for our energy system in the future - even with an increasing share of renewable energies. For technical implementation, the interaction of the various information technology components in particular will be the subject of further developments. Further exchange on the basic instruments is necessary at expert level in order to bundle and transfer knowledge, but also to be able to react to new requirements.

9 PV-SYSTEMS ENABLERS FOR ADVANCED SERVICE AND FLEXIBILITY: STORAGE AND COMMUNITY/VPPs

In this section we will focus on enablers for PV-systems that will help the integration of PV systems within the grid using advanced services. The two main enablers are the **physical storage** (mostly batteries) and **Virtual Power Plants** (VPPs).

9.1 Introduction

We first have a general discussion about batteries and communities/VPPs.

9.1.1 Batteries

9.1.1.1 Large battery system

Using batteries for storage will help the advanced services but as batteries are expensive, the sizing/design of such system is challenging. In [135] six inter-related factors are mentioned:

1) The capacity of the access link that connects the farm to the rest of the grid: the smaller this capacity, the higher the possibility of curtailment, and the greater the need for storage.
2) The power level committed to by the farm owner in each market time slot: the higher the commitment level, the higher the probability of not meeting this commitment, and hence the greater the need for storage.
3) The penalty: the higher the penalty, the greater the motivation to either choose a lower commitment level or to store energy to prevent a future shortfall.
4) The degree of fluctuation in the purchase price in different market time slots: the greater the fluctuation, the larger the benefit from storing solar production for future sale at a higher price.
5) The degree of variation in solar energy during a single market time slot: the greater this variation, the greater the need for storage.
6) The solar generation prediction accuracy: the lower the prediction accuracy, the greater the need for storage to mitigate against prediction errors.

9.1.1.2 Stationary home battery system and vehicle2grid

Stationary batteries are currently the main electricity storage for a home/building. Those batteries are easier to pilot than the battery from a vehicle as they are always plugged. As their price have dropped in the recent years, they are becoming more economically viable as explained in [136] and [137]. Those studies also show that the state Policy play a big part on the return on investment to have a battery.

With the fast penetration of electrical vehicles, home/building batteries will probably not be the main storage in homes/buildings. IRENA [103] anticipate that by 2050, around 14 TWh of EV batteries could be available to provide grid services, compared to just 9 TWh of stationary batteries. The grid2vehicle is already very well implemented for home, parking, workplaces… but the vehicle2grid is not that widely available in many countries due some technical and legal constraints.

9.1.2 Communities/VPPs

From a technical and regulatory point of view, it seems complicated/unrealistic to individually pilot your own battery/load shifting to provide advanced services to the grid. Most of the studies we found propose to operate at community/aggregator level. This is also called Virtual Power Plant (VPP) – see Figure 2.

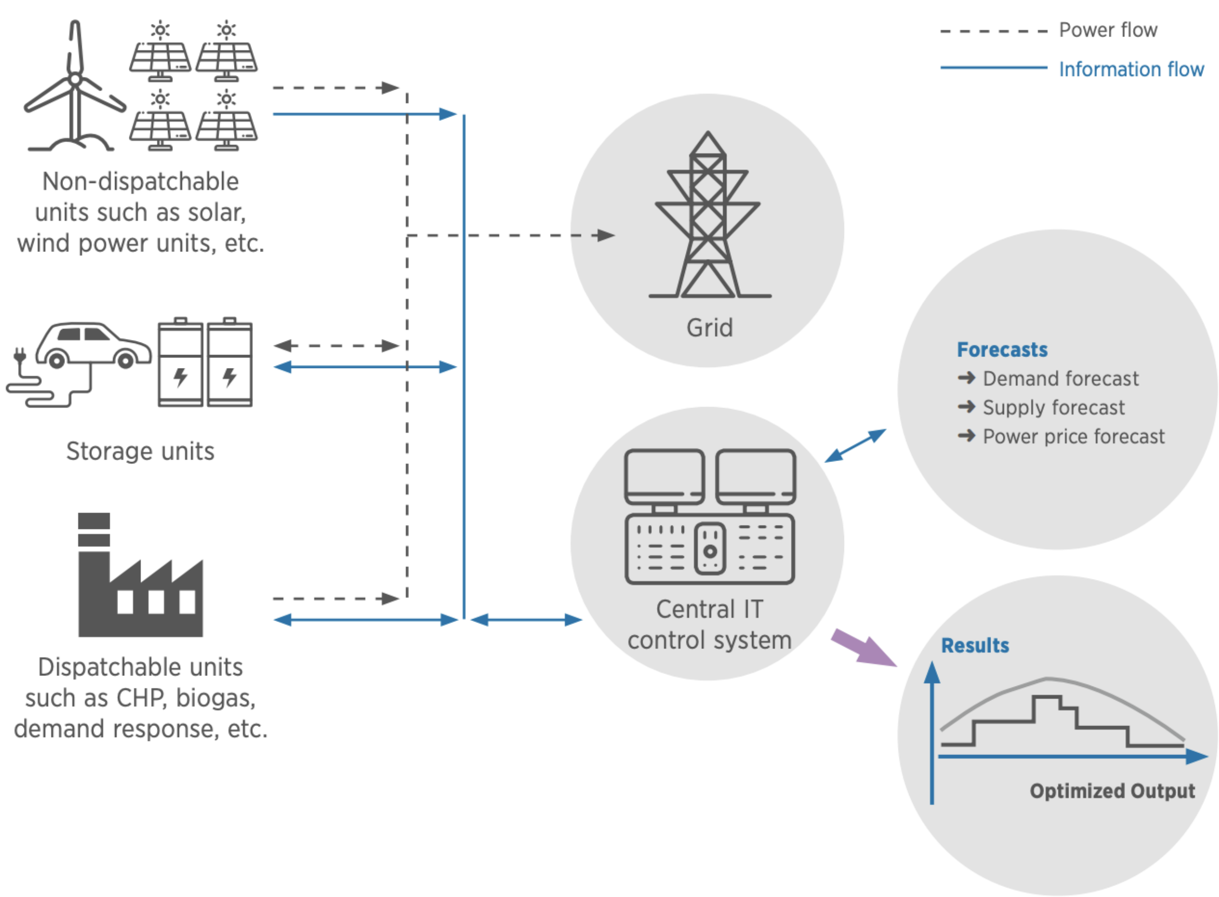

Figure 2: Overview of an aggregator/VPP (taken from IRENA publication [138])

9.2 Increasing self-consumption

As stated in [139], buildings as prosumers have an important role to play with the grid due to their potential flexible energy consumption. The immaturity of the current aggregation market (regulations and policies) with unclear incentives is still a challenge for buildings (especially with small energy consumption).

In [136], several policy options and incentives are studied for the UK market to show the impact they would have on the profitability of a PV system with and without battery. If we want an easier/better integration of PV systems into the grid, such incentives would help people to invest in batteries. Dynamic pricing is playing an important part in the equation. As a full dynamic pricing would be complicated to handle for end consumer (spot market prices are very volatile), the aggregator is playing a key role as an intermediary player. It has to simplify the offer for the end consumer and cover the risks. To limit their risks and be more profitable, aggregators need to find ways to better control grid consumption and injection (pilot their appliances, communication to end-users to change their habits…).

In a house/building, there are few appliances that consume a fair amount of energy and could be scheduled at a time that would help the grid balancing:

- Electrical water heater
- Heat pump
- Pool pumps
- Washing machines
- Dryers
- Electric cars charging

Few appliances can store energy and are therefore easier to optimise as they can be shifted few hours before or after initially planned as for the charging of the battery of an electrical car. Electrical water heaters (very popular in France) are also called Thermostatically Controlled Loads (TCLs). It has been shown in [140]–[142], that the aggregate flexibility offered by a collection of TCLs can be succinctly modelled as a stochastic battery with dissipation and therefore can provide similar advanced services to the grid.

For other appliances the Quality of Service (QoS) needs to be considered [143]. The smart-home user can usually setup his preferences (minimum acceptable temperature at home, time for the washing machine to end…).

Ideally the aggregator should be able to get many data about the homes it manages:

- appliances to be planned during the day
- expected consumption
- expected PV production
- electricity prices during the day
- …

With all those data, the aggregator can build a system to control the appliances inside the houses that will provide advance services to the grid. An example of such system is described in [143] (Figure 3 extracted).

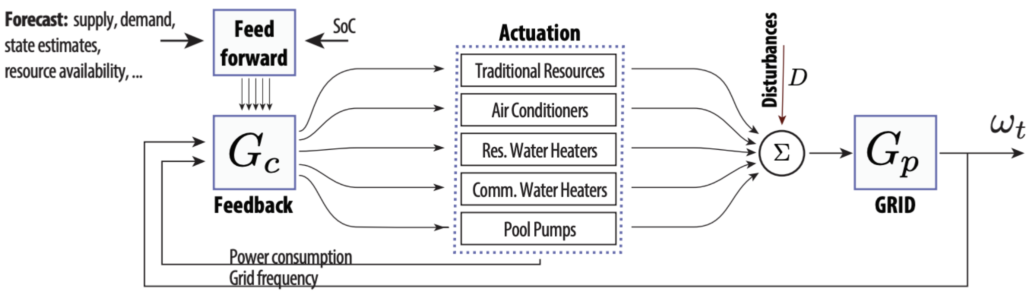

Fig. 2. The control architecture: feedforward commands are computed from forecasts and feedback commands are computed from real-time error.

Figure 3: System to control appliances for advanced services – taken from "Balancing California's Grid Without Batteries" [143]

Many communities/VPPs already exist, in [144] IRENA stated that they are about 2,400 REScoops across Europe in 2014. We summarized the most known ones per country (not only full PV ones) below

Table 23: List of few community projects per country.

Country	Summary
Germany	- Sonnen (in many countries but mainly in Germany): Consists of about 10 000 customers with solar PV generation, battery storage, or both.
France	- Enercoop In February 2021: 100,000 members 7% PV, 53% Wind, 39% hydro, 1% biomass
Spain	- Som Energia In January 2019: 54,300 members and in February 2022: 80,890 members (24.6 GWh/year) - Goiener February 2020: 15,666 members

Belgium	– Ecopower In 2017: 50,000 members with 40% with PV on their building In October 2021: 64,114 members – Courant d'Air: 2021: 2,800 members – Rescoop.eu "Renewable Energy Sources Cooperative"
UK	- Energy4All 2021: 16,880 members

9.3 Frequency support with VPPs and Energy Storage Systems

One of the core responsibilities of a transmission system operator is the real-time control of mismatches between the injection and offtake of electric power, i.e. frequency control/support.

Different European grid operators use different types of frequency support services, but a harmonisation effort is currently underway. Broadly speaking, most member states have services that fall under the following categories: FCR (Frequency Containment Reserve), aFRR (automatic Frequency Restoration Reserve), and mFRR (manual Frequency Restoration Reserve). In Deliverable D1.1 of the SERENDI-PV project, these services have been discussed in detail.

Whereas these services have historically been provided by large (fossil fuel) power plants, technological innovation is offering an alternative way to provide reliable and low or zero carbon balancing power. Two main technological innovations are Virtual Power Plants (VPPs) and the cost reduction of grid-scale energy storage (usually lithium-ion technology).

Virtual Power Plants have been around in Europe for more than a decade and have steadily increased their contribution in grid balancing in member states where the regulation allows for it. Project partner Next Kraftwerke, founded in 2009, reached a milestone of aggregating 10 GW over more than 10 000 individual assets in its Virtual Power Plant in 2022. These mostly renewable assets are pooled together to reliably provide frequency support services to European TSOs or to be traded more effectively. As such, they provide new revenue streams for renewable and/or decentralised assets and help phase out the dependency on fossil fuel plants for system balancing.

Battery Energy Storage Systems (BESS) have also started to make a noticeable contribution to system balancing in the last couple of years. With costs driven down as a result of the upscaling of battery manufacturing for electric vehicles, grid-scale batteries are being built with increasing speed and scale in several European member states. They are applied for a range of different use cases and frequency support is often among them. In the table below, we list a number of projects that illustrate the use of battery energy storage for system balancing.

Furthermore, we can mention a cross countries project: PICASSO: "European aFRR (automatic Frequency Restoration Reserves "Secondary Reserve") mutualisation project, currently being rolled out in Europe (France, Germany, Italy, Switzerland, Belgium 2022, Others 2023/24). Project will allow European countries to share their balancing energy. Led to implementation of storage-compatible market rules in many countries such as Belgium, France and Spain. Aims to lead to reduction in the costs of reserves by sharing resources across different countries." [145].

Table 24: List of some frequency support projects per country

Country	Summary with references
Germany	• Sonnen operates a Virtual Power Plant of household battery systems. They developed control systems to allow participation in the German reserve power markets [146]: "The software is based on the recently amended minimum IT requirements of the four German transmission system operators (TSOs). Sonnen is now able to operate its virtual power plant, which consists of thousands of home storage systems throughout Germany, up to 90% more cost-efficiently. Grid services such as Frequency Containment Reserves (FCR, previously "primary control power") can thus be provided in a permanently stable and significantly more cost-effective manner." • Bordesholm Battery is a 10MW/15 MWh energy storage project located in Bordesholm, Schleswig-Holstein [147]. "This investment, coupled with a BioGas Plan, provides electricity to the 7,500 people inhabiting the community which has the target to meet 100% of its demand with renewable energy sources by 2020. The primary role of this BESS is to help stabilize the regional network (frequency containment reserve), and to provide back-up power. In case of a grid outage, it can help putting back the grid in operation (Black Start) and enable the operation of an independent local grid (Islanding)."
France	• A solar farm will contribute to the frequency support, it is designed by Saft which is TotalEnergies' battery affiliate [148]: "Saft has been awarded a major contract by Neoen, the leading French independent producer of renewable energy, to deliver a turnkey 8MW/8MWh ESS project in Antugnac, (southern France). The facility will be the first co-located ESS and solar farm connected to RTE's French high-voltage transmission grid and will provide vital frequency regulation services to enable Neoen to meet its contractual commitments under RTE's Long Term Call for Tenders scheme (AOLT)." • The biggest battery, also by Saft, is installed at the end of 2021 in Dunkerque. Its power/capacity is 61MW/61MWh: [149] "The projects provide a combination of ancillary services and capacity market services for RTE, with primary frequency regulation, aka Frequency Containment Reserve (FCR) or Primary Control Reserve (PCR), being the main ancillary grid service." "That 10-second data sent to the transmission system operator (TSO) includes 25 separate data points such as voltage, frequency and reactive power. Battery system health data points such as State of Health (SoH), State of Charge (SoC), system temperature and battery ageing are also closely monitored." One can also find some details for the future in a study about the future of storage in France for 2050 in [6].

Spain	• ALMACENA Project (2013): 1MW/3MWh [150]
	    o Power-frequency control
	    o Load shifting
	    o Voltage control
	• Navarra, Northern Spain, 2017: 0.7-1MW/0.39-0.7MWh [151]
	"The project has two battery packs – one for fast-acting response, the other is

	slower. The former is a 1MW / 0.39MWh battery, to deliver 1MW of energy for 20 minutes, while the other is a 0.7MW / 0.7MWh device that can output 0.7MW of energy for one hour." "It will also assess the use of energy storage for ancillary (grid) services such as frequency control and in meeting demand for power in peak periods." In 2021, the Spain roadmap foresees [152] ramping up its storage capacity from the current 8.3GW level to 20GW by 2030 and then 30GW by 2050.
Belgium	• Terhills battery project: 18.2MW / 21.7 MWh [153] "140 large lithium-ion batteries from Tesla and has been integrated into the primary reserve. The key to the project is that software provider REstore has intelligently linked the battery system to other industrial consumers, creating one large virtual power plant of 30 to 40 MW" "In addition to putting power on the grid when frequency is low, the battery installation also charges by absorbing power when there's too much energy on the grid." • Bastogne EStor-Luxproject: 10MW / 20MWh [154] Lithium-ion battery energy storage system that will take part in the secondary reserve service organised by Belgian TSO Elia. • Many VPP projects from Next [155]: up to 14k units and 10.6 GW.

9.4 Grid support

The grid support consists of dealing with overloading problems / too high voltage in the grid.

Table 25: List of some grid support projects per country

Country	Summary with references
Germany	• Sonnen (VPP) can store the excess of energy in a region to support the overloading: [156]. "sonnen has put another virtual power plant (VPP) into operation in northeastern Germany, thus supporting the regional power grid with new technology. If too much wind energy flows into the grid, the sonnenBatteries in that region will store the excess energy. The home storage systems are primarily used in private households for their own clean solar power supply. In addition, the sonnenBatteries are networked with each other to form a virtual power plant, a distributed large-scale storage system. If more wind energy is produced than is needed for consumption, sonnen's VPP can act as a flexible element to absorb the wind power from the grid." • Bordesholm Battery is a 10MW/15MWh energy storage project located in Bordesholm, Schleswig-Holstein [157]. "This investment, coupled with a Biogas Plan, provides electricity to the 7,500 people inhabiting the community which has the target to meet 100% of its demand with renewable energy sources by 2020. The primary role of this BESS is to help stabilize the regional network (frequency containment reserve), and to provide back-up power. In case of a grid outage, it can help putting back the grid in operation (Black Start) and enable the operation of an independent local grid (Islanding)."

France	• Multisite RTE RINGO project - 10 MW/30MWh: [1] "French grid operator RTE is using a Saft energy storage system, a world-first trial project that will evaluate the technique of virtual power transmission. RTE will use different energy storage technologies at three locations on the grid. Saft and its partner Schneider Electric will deploy a lithium-ion (Li-ion) with power conversion and control systems" "One or two of these sites can inject power into the grid while the other site releases it simultaneously. In effect, this acts as a virtual power line, transmitting power to where it is needed and overcoming congestion on the grid at peak time."

Spain	• ALMACENA Project (2013): 1MW/3MWh [150]
	  ○ Power-frequency control
	  ○ Load shifting
	  ○ Voltage control
	• Arañuelo III – Almaraz: 3MW/9MWh [158]
	"The plant is the first large scale solar plant to incorporate batteries in Spain and the storage system is the first of its kind being installed within the photovoltaic plant in a distributed manner, following a DC-coupling configuration."

Belgium	• Balen project – 25MW/100MWh [159] "The construction of the Balen project is planned for late 2021, with completion by 2022. Utilising lithium-ion battery technology, the project will provide grid stability and balancing services for the Belgium grid, as well as help shift renewable energy production into high energy demand periods."

9.5 VehicleToGrid (v2g)

VehicleToGrid can be done at different scale: individual home, small building, or larger scale (i.e.: large commercial/company parking lot).

Table 26: List of some VehicleToGrid projects (v2g) per country

Country	Summary with references
Germany	Volkswagen has an offer in 2022 called "We Charge" that allow end users to plug their car to the network: [160].
France	In France there are very few v2g projects as of 2022. RTE (the network operator in France) need to certify the solution from the industrial: [161]. There is a EDF offer for companies but not yet for end users: [162].
Spain	In Spain there are several V2G schemes in place where electric cars can provide electricity to the building they are plugged in to, although not necessarily into the grid itself. The first V2G charger from Nuvve was installed in 2019 at Molins de Rei [163]. "The solar carport has one 10kW charger equipped with Nuvve's V2G software that allows the energy from the solar panels to be stored inside the car's battery and then be used by the building when the electricity is most expensive (typically at the end of the afternoon and early evening)"
Belgium	• BD4OPEM is an EU H2020 research and innovation project, one pilot site in in Belgium [164]. "As a customer of the local DSO, the Brussels Health Campus is a well-advanced

	energy island owning and running a micro-grid that is able to operate in "island" mode for five consecutive days. The hospital and part of VUB is a critical environment where grid security is highly prioritised. o Smart meters o Topology & Observability of LV network o Client clustering and consumer profiles (patterns & consumption) o SCADA, GIS, Analysers o PV generation + Energy storage + EV charging" • Sweco: 22 DC V2G Chargers (using equipment from Yuso, Elia, ABB) will be installed to charge a fleet of company cars [165]. There will be 3 associated services: o Frequency Response o Reserve o Time shifting for energy users
Finland	The EV charging platform Virta in partnership with Helen, the largest energy company in Finland and Nissan have installed a public bidirectional EV charging point in Helsinki, next to a solar power plant and an electricity storage facility. The charger supports CHAdeMO plugs with 10 kW charging-discharging capacity. The project is part of the government's plan on the utilisation of smart energy storage [166].

You might want to have a look at this website aiming at collecting v2g projects/reports around the world: https://www.v2g-hub.com/. It is not exhaustive but it gives an overview of many projects.

9.6 Gap analysis

9.6.1 Home/building self-consumption

Self-consumption could be improved with:

- More accurate and reliable irradiation predictions to better schedule appliances to maximise self-consumption. It will become even more important for the end user with the global generalisation of dynamic pricing. The prices might become very volatile as they will reflect the price variation in the spot markets (day-ahead and intraday markets) at intervals at least equal to the market settlement frequency.
- More interaction with the prosumer by informing about higher/lower PV production than expected, ie: propose better window of time to use non-piloted appliances in a home or a building.
- More reactive to change in PV production and/or consumption to adapt existing appliances schedule
- More VPPs/communities to help balancing the grid

9.6.2 Frequency support

Unfolding the bottlenecks preventing solar power to deliver ancillary services, the issues with regulatory frameworks and grid codes has been brought up. These should frequently be examined to reflect the state-of the-art. Historical biases to fossil fuel power plants should be removed as to create technology neutral markets in which renewables can fairly compete. As a further gap, the lack of standards when it comes to advanced grid support functionalities including joint testing mechanisms and quality criteria has been raised as concerns. The subject of baseline methodology and related measurement techniques comes to mind.

Additionally, current prequalification and procurement procedures as well as products specifications procedures can hinder PV systems' participation in ancillary services. The current ancillary service products are not necessarily the best fit for PV systems, which is why an update of market design or the development of new products has been presented as a solution. [167]

9.6.3 Grid support

Several studies have shown that the battery storages can support the grid operation, like supporting the voltage stabilities or reducing the overloading of some grid components (e.g. [168], [169]). However, the cost of battery storages can be higher than other measures for grid support considering the short lifetime of a battery compared to a transformer of a cable as grid strengthening measures. With the expected maturity of the battery technologies and therefore the reduction of its costs, the implementation of the battery storages for the grid support should be investigated as a good option.

9.6.4 VehicleToGrid (v2g)

The VehicleToGrid is a quite fast evolving subject with many differences depending on the country. There is a technical side and regulatory side of it. In most European countries v2g is still not allowed. As most of the projects and/or pilot projects are fairly new, there are many opportunities for new actors and solutions to be developed in many countries once the regulators will allow it.

10 SUMMARY AND OUTLOOK

This deliverable summarizes relevant information regarding the technical constraints of high PV contribution in the power grid based on the state-of-the-art and considering several EU-countries. In general, grid integration issues as well as the communication and data management of PV was discussed in this deliverable. In all considered countries the integration of PV and other renewable resources leads to a need for measures like grid extension, which is required in order to keep the operation at normal conditions. These measures lead to high costs, especially considering the aim of 100% renewable energy in the future. To reduce these costs, some technologies should be implemented, such as the provision of ancillary services from PV, installing battery storage systems, smart control of PV through the active communication with PV-inverters. In addition, the transition from a centralized power system with some hundreds of large power plants to a power system with millions of small energy sources requires high transparency regarding the PV and grid data. These topics were briefly explained in this deliverable and discussed based on the state of the art and based on the experience of the project partners.

In WP6 of SERENDI-PV these important topics will be investigated with much more details as follows:

Task 6.3: investigates the communication with PV and the management of PV data

Task 6.4: investigates the smart control of PV and the transparency in the grid through the real-time state estimation

Task 6.5: investigates the possibilities and advantages of storages implementation in the grid

Task 6.6: investigates the possibilities and advantages of providing ancillary services from PV.

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