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D1.2 Assessment and characterization of the current PV fleet capabilities and regulatory environment for grid integration

T1.2 Assessment of the European PV Fleet Capacity and regulatory environment

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Summary

This deliverable is part of the first work package of the SERENDI-PV project, which assesses the global perspectives on PV reliability, PV performance, and the integration of PV in power systems. More particularly, this deliverable focuses on the assessment of the European PV Fleet Capacity and the regulatory environment in which PV systems in Europe must operate. This deliverable is an output of task T1.2.

Document Information

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Lead Beneficiary	Next Kraftwerke Belgium (NKW)
Authors	Elias De Keyser, Nadia Wiesé (Next Kraftwerke Belgium)
Contributors	Next Kraftwerke Belgium (NKW), Tecnalia (TEC), Becquerel Institute (BI), QPV, My Light Systems (MLS)
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1 Executive Summary

1.1 Description of the deliverable content and purpose

This deliverable is part of the first work package of the SERENDI-PV project, which assesses the global perspectives on solar PV reliability, PV performance, and the integration of solar PV in power systems. More particularly, this deliverable focuses on the assessment of the European PV Fleet Capacity and the regulatory environment in which PV systems in Europe must operate. This deliverable is an output of task T1.2.

An overview of the European PV fleet capacity is presented, showing the current state of the solar PV production park in each Member State. A differentiation based on the PV technology and system size is made, which reveals the significant differences between Member States. Besides the assessment of the fleet capacities in different countries, an inventory of the most important national support schemes is presented.

To keep track of the PV installed PV systems, most European Member States make use of one or more databases. They are usually operated by DSOs and/or TSOs to store valuable information about PV (and storage) systems installed in their grid area. An overview of these PV databases, their technical granularity, and the ways the data are collected, and how they are shared between stakeholders is provided in this report.

A number of new grid service KPIs are being proposed, which can indicate the ability to provide ancillary services with a specific PV system. These KPIs could provide guidance for the design of new regulatory frameworks and policies.

Looking at the regulatory frameworks affecting solar PV systems in Europe, the rules for the connection of solar PV assets to the grid and their participation in ancillary services has been assessed. Grid connection requirements have been harmonized in Europe with the 'Requirements for Generators', and a selection of noteworthy requirements is discussed in this report. Since some of these requirements still leave a lot of freedom for national regulatory agencies and grid operators, a selected number of Member States are evaluated in more detail. The result is an assessment of which requirements all solar assets are expected to meet, and which ones might be obligatory depending on the Member State.

The report then discusses the important subset of grid services called balancing power, which are contracted by TSOs to support frequency control. Solar PV does not yet actively participate in these balancing products, and this deliverable presents the identified barriers in the design of balancing products. An overview of current pilot projects and studies that investigate the participation of solar PV is given, which indicate the interest of grid operators for solar PV to participate more actively in system balancing. Finally, a number of suggestions are made to improve the design of balancing power mechanisms and the potential introduction of new balancing products in the future.

1.2 Reference material

The main document used for the elaboration of this deliverable is the Grant Agreement 953016. Besides, the output of the meetings and discussions held inside WP1, and the bilateral meetings with several partners, have served as a basis for the execution of the task T1.2, of which this deliverable is the output.

1.3 Relation with other activities in the project

This deliverable provides an overview of both the current composition of the European PV fleet and its regulatory environment. As such, it serves as a basis for several other tasks within the SERENDI-PV project. The most important ones are listed below in Table 1.1, which depicts the main links of this deliverable to other activities (work packages, tasks, deliverables, etc.) within the SERENDI-PV project. The table should be considered along with the current document for further understanding of the deliverable contents and purpose.

Table 1.1: Relation between current deliverable and other activities in the project

Project activity	Relation with current deliverable
All	The current deliverable feeds from all project activities and work packages.
WP1	The current deliverable feeds from discussions conducted in several other tasks in WP1, especially T1.1. This deliverable can also be considered as useful background information for T1.3 and T1.4.
WP2	The current deliverable can be considered as useful background reading for T2.6.
WP5	Outcomes of the tasks of WP5 can be considered in relation to the current deliverable; advances in power forecasting directly influence the ability of solar PV to participate in ancillary services given their product and auction timelines.
WP6	The findings presented in the current deliverable directly serve as a starting point for some of the work in WP6, in particular T6.2, 6.3 and T6.6.
WP7	The findings presented in the current deliverable feed into the discussions in the context of T7.4 and T7.6.
WP8	The current deliverable can be considered a useful background reading to contextualize the demonstrations conducted in T8.3 and T8.4.

1.4 Abbreviation list

A list of abbreviations used in this deliverable is shown in Table 1.2.

Table 1.2: Abbreviation list

Abbreviation	Meaning
aFCR	automatic Frequency Containment Reserves
aFRR	Automatic Frequency Restoration Reserve
BESS	Battery Energy Storage System
BSP	Balancing Service Provider
DSO	Distribution System Operator
ENTSO-E	European Network of Transmission System Operators for Electricity
FCR	Frequency Containment Reserves
FIP	Feed-In-Premium
FIS	Feed-in-System
FIT	Feed-in-Tariff
KPI	Key Performance Indicator
mFCR	manual Frequency Containment Reserves
MS	Member State
PPM	Power Park Module
PV	Photovoltaics

Abbreviation	Meaning
PVPS	Photovoltaic Power Systems Programme
RES	Renewable Energy Sources
RfG NC	Requirement for Generators – Network Code
RoCoF	Rate of Change of Frequency
RR	Replacement reserves
SPGM	Synchronous Power Generating Module
TSO	Transmission System Operator

2 Methodology

In this section, the general approach followed to conduct task T1.2 is explained. This provides the reader with a high-level overview of how the findings presented in this deliverable were established. Throughout the report, more details and references are provided.

T1.2 was split up in two subtasks. The first focuses on the assessment of the European PV fleet capacity. Installed capacity data per Member State was obtained from Eurostat [1] and from the partners of this work package. The assessment of different support schemes draws on own analysis of legal documents of Member States and the work conducted in the research project RES Legal Europe [2]. To investigate the use of databases for monitoring solar PV in grids, the work of the IEA's Photovoltaic Power Systems Programme (PVPS) has been used as a starting point [3]. To collect more detailed information, an online survey was set up. The participating parties to this survey were[1]:

- Company A (Lithuanian grid operator)
- Company B (Bulgarian grid operator)
- Company C (Belgian grid operator)
- Company D (Finnish Ministry)
- Company E (Spanish grid operator)
- Company F (Dutch grid operator)
- Company G (Belgian grid operator)
- Company H (French grid operator)
- Company I (Austrian grid operator)
- Company J (Italian grid operator).

To gather more insights in the ways grid operators use these databases, and verify the findings from literature, additional interviews were conducted with the following partners[1]:

- Company H (French grid operator)
- Company I (Austrian grid operator)
- Company C (Belgian grid operator)
- Company F (Dutch grid operator)
- Company J (Italian grid operator).

The main questions used during these interviews are shown in Annex A, while the online survey is shown in Annex B.

In the second subtask of T1.2, an assessment of the regulatory framework for solar PV integration was made. The authors drew on a mix of scientific literature and own experience in several European markets to identify the technical capabilities that allow solar PV to provide system services. For the in-depth analysis of the grid connection requirements, the Requirements for Generators Regulation was used as a starting point [4]. The details of the national implementation of this European Regulation were assessed based on national legislative texts and the ENTSO-E implementation monitoring library [5]. Further insights were gathered from grid operators during the same interviews as mentioned above.

For the analysis of the balancing market design in different Member States and their openness to solar PV participation, the Electricity Balancing Guideline was used as a starting point [6]. National implementation of this Guideline was assessed based on national legislative texts and the ENTSO-E Ancillary Service Survey [7]. Again, these results were verified and extended during the interviews mentioned above.

[1] as this document is a public document, the names of the companies have been anonymized

3 Assessment of the European PV Fleet Capacity and its detailed knowledge by grid operators

3.1 Introduction

Renewable energy should account for 32% of the total energy production in the European Union by 2030 according to the 2030 climate targets set by the European Commission [8]. All over Europe, Member States invest in renewable energy resources to achieve these goals with a rapid growth rate of solar PV as one of the results. At the end of 2019, 118 GW solar PV capacity was installed in the European Union, resulting in an annual energy production of 120 TWh which was 4% of the total electricity production in 2019 [1].

To reach these Renewable Energy Source (RES) targets and incentivize investments in solar PV installations, each Member State is entitled to implement his own policies (as long they are in line with state-aid rules and the European Energy Directives). To do so, governments across Europe provide financial support for PV systems under several types of support mechanisms, such as feed-in tariffs or premiums, net metering schemes and tax reductions.

Due to this solar PV evolution in Europe, grid operators are challenged to maintain and ensure a stable and safe operation of the electricity grid. Transmission and distribution system operators (DSOs and TSOs) in Europe keep track of the impact of solar PV by storing valuable information about PV systems connected to their grids in databases. In order to facilitate the integration of solar PV in the electricity grid, it is of great importance for grid operators to minimize the impacts of solar PV with the use of ancillary services. It is in their interest to search for more innovative methods to maintain a safe operation of the grid, such as the provision of grid services by PV systems.

Within the context of this study, several interviews were carried out with grid operators in Europe to discuss the current impact of solar PV in their grids, solar PV databases and (future) ancillary services with solar PV. The interviewed parties were: *Company H* (French grid operator), *Company I* (Austrian grid operator), *Company C* (Belgian grid operator), *Company F* (Dutch grid operator) and *Company J* (Italian grid operator).

In addition, a survey about solar PV databases and the parameters they include was carried out, to evaluate the landscape of approaches in Europe in keeping track of the growth of solar PV installations. The participating parties to the survey were: *Company A* (Lithuanian grid operator), *Company B* (Bulgarian grid operator), *Company C* (Belgian grid operator), *Company D* (Finnish Ministry), *Company E* (Spanish grid operator), *Company F* (Dutch grid operator), *Company G* (Belgian grid operator), *Company H* (French grid operator), *Company I* (Austrian grid operator) and *Company J* (Italian grid operator).

In Section 3.2, an overview of the current state of the European PV fleet will be provided by assessing the capacity of the existing fleet, per system size, sector and system type including floating PV and Building-integrated PV (BIPV). Further, the support mechanisms for PV are discussed in Section 3.3, including their relation to the current types of installed PV plants in the Member States. Further, databases used by grid operators to keep track of the developments in their grid are analysed together with the data exchange between DSOs and TSOs in Section 3.4. Lastly, several KPIs are presented in Section 3.5 which indicate the ability of a solar PV system to deliver ancillary services.

3.2 European PV Fleet Capacity Assessment

This Section maps the current PV fleet capacity in the European Union and how it is distributed among the different Member States. The PV solar capacity will be expressed in absolute and relative numbers compared to the total production capacity installed in Europe. Further, a segmentation of the PV fleet per technology and per sector is presented. It will discuss shortly the relation between the segmentation and the used support schemes in the Member States, which will be described in Section 3.3

3.2.1 Absolute European Installed PV Capacity and Annual Energy

According to the data of Eurostat [1], 118 GW of installed PV capacity was realised at the end of 2019 in the European Union, and 120 TWh of electricity was produced by solar PV throughout 2019. Ranking the EU Member States based on installed capacity, brings Germany on top of the list with 49 GW installed solar photovoltaic capacity. Other flourishing solar markets expressed as absolute numbers, are Italy with 21 GW and France with 11 GW. Latvia and Ireland invested less in solar PV and have an installed capacity of respectively 3 MW and 31 MW. Since solar PV data for 2020 was still incomplete at the time of writing, the numbers of 2019 are presented. However, a table with the installed solar PV capacity per country is presented in Annex C for the year 2020.

Table 3.1: Overview of the installed PV capacity and annual produced energy by PV at the end of 2019 (data source: [1])

	Installed PV capacity 2019 [MW]	PV energy production 2019 [GWh]
EU 27 countries (no UK)	118,078	120,035
Ranked by capacity		
Germany	49,045	46,392
Italy	20,865	23,689
France	10,795	12,225
Spain	8,973	9,420
Netherlands	7,177	5,335
Belgium	4,637	4,247
Greece	2,834	4,429
Czechia	2,086	2,312
Austria	1,702	1,702
Poland	1,539	711
Hungary	1,400	1,497
Romania	1,398	1,778
Denmark	1,080	963
Bulgaria	1,048	1,442
Portugal	901	1,342

	Installed PV capacity 2019 [MW]	PV energy production 2019 [GWh]
Sweden	714	679
Slovakia	590	589
Slovenia	264	303
Finland	222	147
Luxembourg	160	130
Malta	154	212
Cyprus	151	218
Estonia	121	74
Lithuania	103	91
Croatia	85	83
Ireland	31	21
Latvia	3	3

3.2.2 Relative share of PV capacity in total production capacity

To better reflect the current situation of the power system, the share of PV production capacity with respect to national total installed production capacity is shown below in Figure 3.1. Although Germany has installed the most solar PV capacity in absolute numbers, the Netherlands scores the highest when it comes to the relative share of PV production capacity with 28.3%, followed by Belgium with 26.3% and Malta with 26.0%. Malta's PV energy production exceeded 10% of its national annual energy production, followed by Greece with 9.8%, showing the advantage of their geographical location compared to other Member States. Northern countries installed less solar PV on average than Southern countries. The share of PV in the total installed capacity in the European Union, respectively total annual produced energy, is 13.5% and 4.1%.

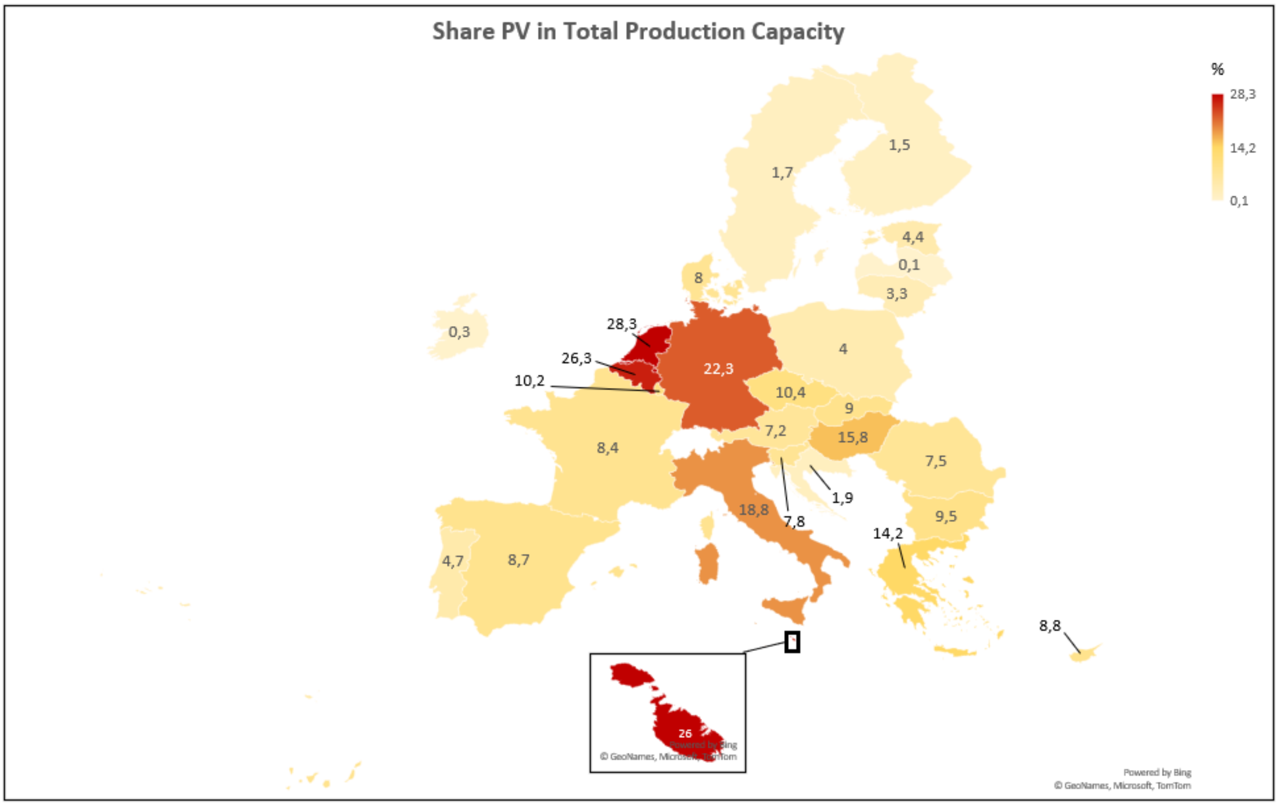

Figure 3.1 : European map showing the PV capacity share (%) in the total national installed production capacity (data source: [1])

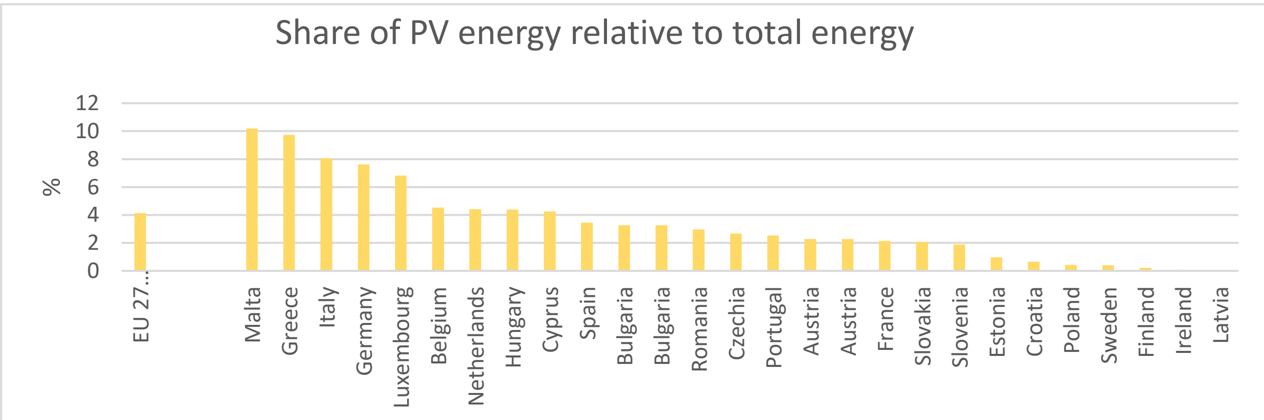

Figure 3.2 : Total EU PV energy share and national PV energy share in the total annual produced electricity in 2019 (data source: [1])

3.2.3 Installed Capacity per sector per Member State

The allocation of the installed capacity to each sector segment is presented in Figure 3.3. The segmentation is based on system size and data from EUROSTAT [1]: Residential (<20 kW), Commercial and Industrial (20 kW - 1000 kW),Utility-scale (>1000 kW) and off-grid. This is similar to the method of Solar Power Europe [9], except for the capacity size which split residential and commercial systems at 10 kW instead of the SERENDI-PV approach at 20 kW. Future studies would benefit from a standardized segmentation in order to have the ability to align and compare the results better.

According to Solar Power Europe the segmentation still reflects the historical support mechanisms for solar PV in each Member State [9]. Countries with a high share of utility PV installations provided interesting Feed-In Tariffs, incentivizing large PV system investments. However, [10] states that the design of support schemes was not able to follow the rapid growth of PV markets in some Member States, leading to an uncertain support scheme landscape and decreased investment confidence because of unpredictable changes of the support schemes taken by governments. This was the case for Romania, Bulgaria and Czech Republic and (until 2018) Spain [9].

In some Member States, such as Belgium and Austria, support schemes were mainly directed towards (residential) rooftop PV, leading to a solar PV park dominated by residential systems [9].

The next Section will give an overview of these existing support mechanisms in the European Union and indicate currently used financial support schemes in the European Member States.

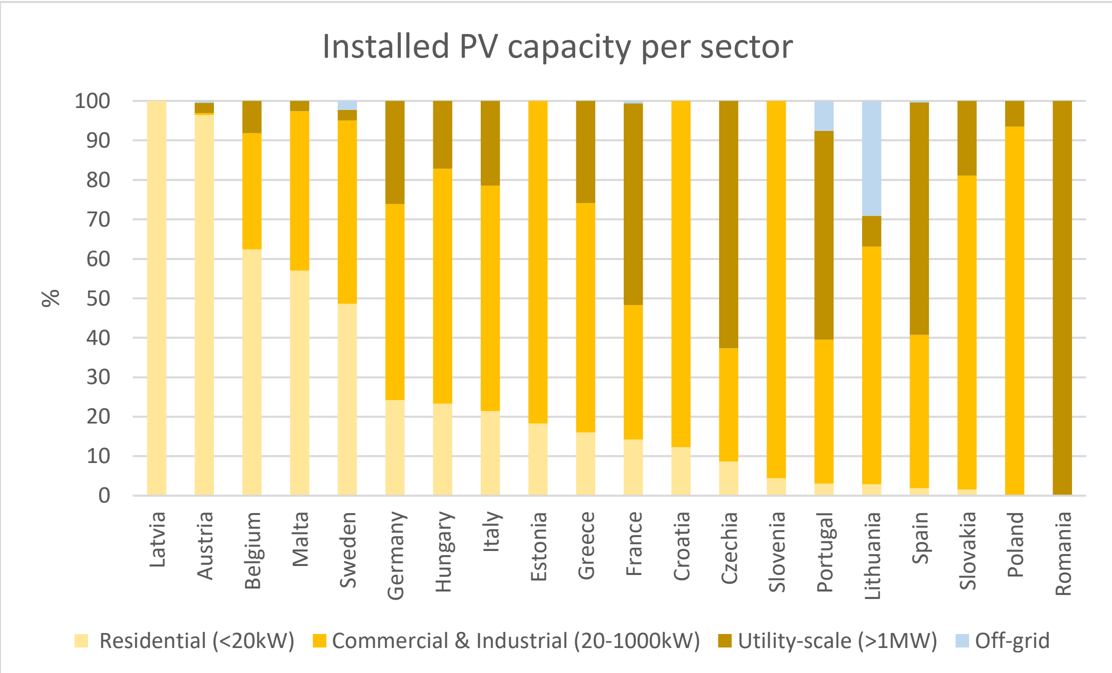

Figure 3.3 : Overview of the installed PV capacity per sector in the European Member States (data source: [1])

3.2.4 Installed capacity per technology

The European solar market is mostly dominated by rooftop and ground-mounted PV. New technologies, like floating PV (FPV), are installed in several countries, but still account for a very small part of the total installed capacity. Examples of installed floating PV systems can be found in Belgium, France, Italy, the Netherlands and Portugal. Distributed PV is represented by mainly building applied PV (BAPV), e.g. rooftop PV, with a smaller amount of Building integrated PV (BIPV), e.g. solar windows [11].

Table 3.2: Overview of installed PV capacity (grid connected) per technology (data source: BI)

Grid connected capacity per technology [MW]						
	Total ground-mounted, FPV (and other*)	**Ground-mounted (and other*)**	**FPV**	**BIPV and BAPV (distributed PV)**	**Off-grid**	**Total**
Germany	7,895.0			41,121.0	-	49,016.0
Italy	11,912.2	11,911.9	0.3	8,953.1	-	20,865.3
France	4,108.0	4,091.0	17.0	5,796.0	30.2	9,934.2
Spain	8,913.0			667.0	330.0	9,910.0
Netherlands	3,737.0	3,710.2	26.8	3,137.0	-	6,874.0
Belgium	122.0	119.8	2.2	4,739.0	-	4,861.0
Austria	18.1			1,676.3	7.7	1,702.1
Denmark	154.7			1,203.8	4.0	1,362.2
Poland	380.0			910.0	-	1,290.0
Portugal	401.0	400.8	0.2	283.0	143.0	827.0
Sweden	30.5			667.5	15.8	713.9
Cyprus	10.6			77.6		88.2

* Agrivoltaic PV could also be included in this category, if there is no self-consumption, but those installations still represent a very negligible share.

3.3 Support schemes for PV in European MS

EU Member States provide financial support to PV installation operators (and other renewable energy plant operators) in order to reach the RES targets. Each Member State is entitled to design his own policies and support mechanisms, leading to different approached in the European countries. Several key support mechanisms which are currently used by governments, will be described in this section:

- Net-metering scheme
- Feed-in-System (FIS)
    - Feed-In-Tariff (FIT): classic or tender schemes
    - Feed-In-Premium (FIP): classic or tender schemes

- Tax reduction, exemption, or deduction
- Quota system: based on (green) certificates trade
- Soft loan or loan guarantee
- Other subsidy

For more detailed information about the support schemes, please refer to [12].

3.3.1 Net-metering scheme

A net-metering scheme allows to net consumed and produced energy over a long time period, such as yearly periods. This is in contrast with self-consumption schemes in which energy consumption is compensated with energy production in real time or in smaller time frames (<=15 minutes) [13].

3.3.2 Feed-in-System (FIS)

A Feed-In-System is a widely used support mechanism in which a producer is reimbursed for his injected energy into the electricity grid at a certain price per kWh [14]. Depending on the type of Feed-In-System, this is a fixed price or a price based on electricity wholesale market prices. The former is called a Feed-In-Tariff (FIT), the latter a Feed-In-Premium (FIP). In some cases of Feed-In-Systems, tenders or auctions are used to allocate the financial support which are addressed here as Feed-In tender schemes.

3.3.2.1 Feed-In-Tariff (FIT): classic or tender schemes

A FIT guarantees a fixed price for the produced and injected electricity into the grid. This can be allocated based on certain requirements, such as the nominal power of the PV installation (often applied to smaller PV plants) or allocated via tenders.

3.3.2.2 Feed-In-Premium (FIP): classic or tender schemes

A FIP guarantees a tariff premium or market premium on top of the electricity market revenues. It covers the difference between the revenues necessary to make the solar plant profitable and the market revenues. In contrast to a FIT, plant operators have to trade their energy on the power exchanges, possibly increasing the revenue risk for the plant operators [15], but incentivizing them to forecast the expected production and balance out their portfolio.

3.3.3 Quota system or quota obligation: based on trade of certificates

A quota obligation forces electricity suppliers to have a portfolio with a minimum share of renewable energy. In contrast to FIT / FIP, the government does not decide on the price of the support scheme, but fixes minimum quantities and let the market decide the price [15]. Certificates are distributed to producers for the renewable energy produced. They can be traded between market parties and are finally used by the suppliers to prove that they meet the quota obligation set by the government.

3.3.4 Tax reduction, exemption, or deduction

Taxes are either fully exempted or partially reduced via a tax credit or tax deduction, e.g.: a tax credit is based on a percentage of the CAPEX, a tax reduction on the delivery and services related to investments in renewable energy plants (for example from the normal 20% to 10%) [2]. Net metering can also be seen as a tax relief if taxes are based on the energy component of the electricity bill. In this study, we will distinguish between net-metering and tax reductions.

3.3.5 Soft loan

Soft loans, loans that are interest-free or include a below-market rate of interest, are given as financial support for investments in renewable energy.

3.3.6 Other subsidies

This category includes different types of subsidies, such as investment grants via tenders or subsidies to PV installations that did a registration (obliged to get a subsidy) and subsidies to technologies or projects that meet certain requirements.

3.3.7 Overview support mechanisms in EU MS

A summary of the support scheme database presented by RES LEGAL EUROPE [2] is formulated in the table below which gives an overview of the support mechanisms currently used in the EU Member States. This database was updated until the end of 2018 but mentions if information is outdated or a change was expected in the future. In these cases, the summary was complemented or updated with new sources which is shown in the last column.

Table 3.3: Overview of support mechanisms for PV utilized in the EU Member States (data source: [2])

Country	FIT	FIP	Net - metering	Quota system (certificat	Tax reduction	Soft loans	Other subsidies	Update source
Austria	X						X	
Belgium			X	X			X	
Bulgaria	X	X						
Croatia	X	X				X	X	
Cyprus			X				X	
Czechia	X	X			X			
Denmark		X	X					
Estonia		X						
Finland		X					X	
France	X	X			X			
Germany	X	X				X	X	
Greece	X	X	X				X	
Hungary	X	X	X			X	X	
Ireland		X					X	[16]
Italy		X	X		X			
Latvia			X					
Lithuania		X		X		X	X	[17]
Luxembourg	X						X	

Country	FIT	FIP	Net - metering	Quota system (certificat	Tax reduction	Soft loans	Other subsidies	Update source
Malta	X	X						
Netherlands		X	X		X	X		
Poland	X			X	X	X	X	
Portugal	X							
Romania				X				
Slovakia	X	X			X			
Slovenia	X	X	X				X	[18]
Spain		X			X			
Sweden				X	X		X	
Total count	14	18	9	5	7	6	14	-

From Table 3.3, it is clear that FIPs are currently very popular in the European Member States. Although FITs and net-metering schemes are also used in quite a lot of the Member States, in most countries these FITs are only granted to small scale PV systems, such as in France (<100kW), Germany (<100kW) and Greece (<10kW) [2]. In the past, also larger PV plants could apply for a FIT scheme, like in Germany until 2016, but these policies were adjusted [10]. Another trend in the last years was the tendering of FIT and FIP instead of granting a FIT and FIP directly (classic FIT and FIP). Tenders for a FIT are used in Slovenia (<10MW) and Poland. In addition, FIP through tendering is common in several countries, such as the Netherlands, France and Croatia. In Germany both classical and through tendering FIP and FIT schemes are used.

Further, a quota system with green certificates is commonly used in Belgium, Lithuania, Poland, Romania and Sweden. Tax reductions and exemptions are used when installing PV in Sweden (<255kW and micro grids) and in Czechia where real estate is exempted from real estate tax. Furthermore, Germany foresees a soft loan scheme for stationary battery storage systems related to a PV installation [2]

In some Member States subsidies are given to a certain sector. For example, in Romania subsidies are granted to PV installations in the agricultural sector and in Luxembourg artisanal, industrial and commercial companies can apply for a specific subsidy [2].

3.4 Databases operated by grid operators

The EU renewable targets and the subsequent increasing penetration of solar PV in the European electricity grid push grid operators in several Member States to keep close track of the developments in their grid. European Member States make use of a database, usually operated by DSOs and/or TSOs to store valuable information about PV (and storage) systems installed in their grid area.

The information in this study about available and operational databases was collected through various surveys and interviews with European grid operators which are active in the countries listed in Table 3.4. The table gives an overview of the PV databases and the level of detail they store per Member State. The structure and included parameters used in the table are adopted from the PVPS study [3] with a focus on the basic data, market data and grid planning and simulation data. In addition, some storage parameters were added to evaluate database information on Battery Electricity Storage Systems (BESS) in the study.

When investigating the different databases, it becomes apparent that the level of detail of the registration parameters varies a lot throughout the different Member States from only basic information, such as administrative data and AC power, to detailed information about PV installations including orientation and ancillary services, which is the case for Spain and Germany.

In Section 3.4.1 the purpose of the database and the obligation to register solar PV installations is studied. This is essential to see if grid operators keep a complete overview of the installed PV in their grids or not. Further, often several databases are used in one-member state. Even though the end use of the database might be different, often the underlying data is overlapping, leading to discrepancies between databases or an ineffective use of them. This is discussed in Section 3.4.2. Shared databases could provide a solution to this problem and is discussed in Section 3.4.3. The exchange of data between TSOs and DSOs is essential to facilitate the integration of PV into the grid, e.g.: forecasting of electricity production and procurement of balancing services, which are the responsibility of the TSO, are also dependent on the injection of solar PV in the DSO-grid. The exchange of data between grid operators can be beneficial for grid operation and planning processes, which is discussed in Section 3.4.4. Further, the accuracy of the current databases and the registration of battery-PV systems are discussed in Section 3.4.5 and 3.4.6. Finally, an overview of the different parameters in the PV databases of the grid operators is given in Section 3.4.7 and recommendations are presented as a conclusion in Section 3.4.8.

3.4.1 Purpose and registration obligation

The databases are used for different types of purposes. In countries such as Belgium and France, owners of PV systems are always obliged to register their installation. Often, this is part of the grid connection requirements and the data is used in grid studies when larger PV plants are registered. Based on the grid study, the grid operator can calculate the connection costs. Some grid operators stress that PV plant registration is crucial for their grid operation and planning.

In Belgium, PV systems smaller than 10kVA are obliged to register when the installation is becoming operational. In that case the DSO does not make an assessment beforehand whether there will be an impact on the grid. For larger systems, a study needs to be requested first before realizing the project. The *Company C* (Belgian grid operator) estimates the impact on the grid first and takes mitigating measures if problems are expected (e.g. cable reinforcement, bigger transformer) before connecting the PV system.

Databases are sometimes used solely for billing purposes and do not contain much detailed technical data, like in Austria. In several European countries, owners or operators of PV systems are obliged to register their PV installation, independent of the size, in a centralized database. Often, PV system operators are only obliged to register if they want to apply for financial support, such as a feed-in-tariff or certificates. In Bulgaria, the database is solely used to register systems when they want to receive government support or certificates of origin. In this case, no obligation is present to register a PV installation, but owners of PV systems are incentivized with financial support. In France, two different types of databases exist. First, data is gathered through the obligatory grid connection application, via a standard form. Second, if a PV installation owner wants to apply for subsidies, additional data is collected in another database with a higher level of detail than the technical database.

3.4.2 Centralized versus decentralized or databases

In several Member States more than one PV system databases is in operation, often with a different purpose. In Belgium and France, the database for subsidies is separated from the one used by the DSO for technical purposes. Also, in the Netherlands information about subsidy schemes is collected by the authorities (RVO) and not the grid operator. In addition to subsidy and support scheme databases, information about PV systems can be found in separate databases including ancillary services and additional storage systems, like in Belgium. The information of PV systems from the different databases can be linked for example using the identification number of the grid connection. In Member States, such as Belgium, TSO and DSOs use a different and separate database.

3.4.3 Database sharing

Most of the grid operators do not make use of a shared database with other stakeholders in the solar and/or electricity sector. Several of them indicated in the interview and survey that although they don't have a shared database at the moment, it would be interesting to have one. The interviewed DSO in Austria made clear that this is only useful for certain use cases and that it can be interesting to share only a part of the database which is relevant for the parties. Other grid operators do not share their database or do not make it public and stress the importance of the confidentiality of the data. The approach varies among the Member States:

- Belgium Spain, France and Italy share certain parts of data with other parties (e.g. government, regulator) by for example aggregating the data and therefore anonymizing the data.
- In Spain, data is shared using web-tools with clients and their suppliers without sharing the entire database.
- In France, aggregated data can be consulted on a public website with a map showing information of installed capacity per department and shares data (in the form of a report) with the ministry which uses the data to evaluate the subsidy scheme.
- In Bulgaria, the "Guarantees of origin database" is public, but it is important to mention that this database contains relatively little detail.

3.4.4 Data exchange between DSOs and TSOs

Forecasting of electricity production and procurement of balancing services are influenced by PV injection. In addition, sizing of grid components, such as MV-LV transformers, is today often dependent on solar PV. Therefore, alignment of correct data between the different grid operators is essential to facilitate the integration of PV in the grid. In the end, grid operators all face similar challenges with respect to monitoring and safeguarding their grids, facilitating the integration of solar PV, procuring flexibility services, and increasing consumer participation in electricity markets [19] Today both TSOs and DSOs would benefit from data exchange between them when PV is impacting or will impact the operation and planning processes of the grid.

During the interviews conducted for this study, it became clear that data exchange between different grid operators is limited. Both *Company H* (French grid operator) and *Company C* (Belgian grid operator) share mostly aggregated data with the national TSO. This data includes information about installed PV power behind each coupling point between the DSO grid and TSO grid. Also, the *Company J* (Italian grid operator), recognizes more work is needed on exchange between DSO and TSO level for data exchange.

In Belgium, PV installations are mostly connected to the DSO grid. DSOs keep a database of the installed PV systems in their grid. All Belgian DSOs provide data input into the TSO's database. Plants which are larger than 400kVA must be entered individually by the DSO in the TSO database (called PISA). Smaller plants can be aggregated, but there is no obligation to register them in the TSO database. It is interesting to compare the differences between the database of the DSO and TSO in the same Member State: it was stated that the data quality for PV is the worst of all possible generation types with up to 20% difference between bottom-up reported values in PISA and installed capacities according to government agencies. It is clear that differences between the rules of registration and the separation of the databases lead to discrepancies in this case.

3.4.5 Accuracy of databases

The PVPS study [3] mentions that the data collection process and the database management vary in quality between the different Member States. It is stated that the data in Belgium has been modified several times retroactively and that the data in France is incomplete because only data of the main DSO is included, and smaller DSOs are not taken into account.

In the Netherlands, a complete overview of all solar assets in the Dutch grid is missing. Information about larger assets connected to the grid is known, but it is observed that grid users of smaller assets do not fill out the registration forms correctly (e.g. fake postal code), which leads to “pollution of the data”. Although there is currently an obligation to register in the Netherlands, there is no real incentive for grid users to fill this out correctly, but the Dutch TSO indicated they would like to see this changed in the future.

3.4.6 Battery systems in databases

It is also interesting to have a look at solar PV systems combined with energy storage. Several countries already collect information about battery systems in their grid, such as battery capacity and inverter power: Italy, Spain and Netherlands. Belgium also gathers this information about battery systems but includes it in another database. *Company H* (France) collects only information about the presence of a battery system connected to the grid, but no further technical information is included.

3.4.7 Parameters in EU PV databases

Table 3.4: Overview of the parameters included in PV databases utilized by EU Member States. “(X)”: not stored in the same database for PV, but available in another database or aggregated data; “((X))”: depending on size; “?”: unknown. (data source Germany and Denmark: [3], data source other: own analysis)

	Belgium	Bulgaria	Finland (PVPS)	Spain	Netherlands	France	Austria	Italy	Germany (PVPS [3])	Denmark(PVPS [3])
General information about the database										
Database for PV systems available and in operation	x	x	-	x	x	x	x	x	x	x
All PV systems (in the concerned region) must be registered in the database	x	-	-	x	x	x	x	x	x	x
Only certain systems (e. g. systems claiming a FIT or systems above a certain capacity) must be registered in the national database	-	x	x	-	-	-	-	-	-	-
Database is mostly available for third parties (e. g. public)	(x)	x	-	(x)	-	x	-	(x)	x	-
Database is strictly confidential	-	-	x	x	x	-	x	-	-	-

	Belgium	Bulgaria	Finland (PVPS)	Spain	Netherlands	France	Austria	Italy	Germany (PVPS [3])	Denmark(PVPS [3])
General data										
Project name e.g. (name new installation)	-	X	-	X	-	-	X	X	X	-
Identification number	X	X	-	X	X	X	X	X	X	X
County	X	X	-	X	-	X	X	X	X	X
City	X	X	-	X	-	X	X	X	X	X
Address	X	-	-	X	X	X	X	X	X	X
Coordinates	(X)	-	-	X	-	(X)	-	X	X	-
Type of Feed-in Tariff (FIT)	-	X	-	X	-	(X)	-	X	-	X
Operational metering data with monthly (or yearly) resolution	((X))	-	-	-	-	-	X	-	-	-
Operational metering data with daily (or smaller) resolution	((X))	-	-	X	-	-	-	-	-	-
Site data (if several databases are in place, ticks refer to most official database)	-	-	-	-	-	-	-	-	-	-
Type of consumer (household, industry, ...)	-	-	-	X	X	X	X	X	X	-
Type of system (rooftop, ground mounted)	-	-	-	-	-	X	-	-	X	-
Technical data										
Type of module	-	X	-	-	-	-	-	X	-	X
DC-power	-	-	-	-	X	X	-	X	X	
AC-power	X	-	X	-	-	-	-	X	X	X
Inverter power	-	-	-	X	X	X	X	X	X	X
Inverter manufacturer	-	-	-	-	X	-	-	-	-	X
All modules have the same orientation (yes/no)	-	-	-	-	-	(X)	-	-	X	-
Orientation	-	-	-	-	-	(X)	-	-	X	-
Tilt angle	-	-	-	-	-	X	-	-	X	-
Ancillary services (yes/no)	(X)	-	-	-	X	-	-	X	X	-
Remote control by DSO	(X)	-	-	X	-	X	X	X	X	X
Remote control by TSO	(X)	-	-	X	-	-	-	X	?	?
Remote control by Market Parties	(X)	-	-	X	-	-	-	-	X	-

	Belgium	Bulgaria	Finland (PVPS)	Spain	Netherlands	France	Austria	Italy	Germany (PVPS [3])	Denmark(PVPS [3])
Remote control by others	(X)	-	-	-	-	-	-	-	X	-
Can be operated in islanded mode	-	-	-	-	-	-	-	-	X	-
Black start capable	-	-	-	-	-	-	-	-	X	-
Type of grid connection (injection only/ self-consumption)	-	-	-	X	-	X	X	X	X	-
Maximum power fed into the grid	X	-	-	X	(X)	X	X	X	X	X
Energy capacity storage if present (e.g. battery)	(X)	-	-	X	X	-	-	X	?	?
Inverter power (battery inverter)	(X)	-	-	X	X	-	X	X	?	?

3.4.8 Recommendations on legislation on integrated databases and transmission of information between DSOs and TSOs

Based on the discussions and interviews with DSOs and TSOs in this project, several recommendations regarding the databases used by grid operators are listed:

- A solar PV database shall be accessible to multiple stakeholders, taking into account privacy and anonymization of data where needed.
- The registration of solar PV systems shall be compulsory, no matter the size. Not only systems that are granted financial support should be registered.
- To reduce the administrative burden and avoid poor quality of the submitted data, registration should be automated as much as possible. For residential systems, it should be carried out by the installer or automatic plausibility checks should be in place.
- A solar PV database shall be shared between DSOs and TSOs or TSOs and DSOs shall interact on a regular and harmonized basis exchanging the needed data [19].
- All data about solar PV systems and the related battery systems shall be collected in one national centralized database instead of several decentralized databases.
- A central database shall substitute or support existing administrative processes [3] by making PV system planning, realization and grid operation more effective and avoiding discrepancies between decentralized databases.
- Solar PV databases shall include administrative and ('static') technical parameters of PV installations in order to be able to use this data in (preliminary) grid simulations, for example to study the grid impact of a new installation.
- Solar PV databases shall include real time measurement data from PV installations or representative measuring points in the grid (e.g. voltages at the end of a feeder, current measurements) to enable the grid operators to have a good overview of the (real-time) impact of solar PV in their grid. It is

recommended that in case of real time measurements of the installations are used, the real time measured offtake behind the same access points and behind other access points in the same grid are also taken into account to get a representative view of the real situation of the grid.

- Real time data shall be available in the solar PV database for both large- and small-scale PV systems connected to the high and low voltage grid or shall include representative measuring points grid (e.g. voltages at the end of a feeder, current measurements) in both high and low voltage grids.

3.5 Grid integration: KPIs on the ability to provide ancillary services with PV

The increasing proliferation of PV systems in the European electricity grids will challenge the grid operators to maintain and ensure a stable and safe operation of the electricity grid. The impact and consequences for the grid, such as congestion problems, frequency and power quality issues described in more detail in report D1.1, will force the grid operator to search for more innovative methods to avoid these situations. Whereas PV systems can put more pressure on the safety of the grid, it is interesting to study the possibilities for solar systems to contribute to the safe operation of the electricity grids by delivering ancillary services and participating in balancing markets.

In the past, ancillary services were offered by conventional power plants, such as gas-fired power plants. However, with the liberalization of the electricity market and the move towards technology neutrality, more opportunities are created for renewable energy technologies to participate.

In this section, several KPIs are presented which indicate the ability of a solar PV system to deliver ancillary services. The KPIs are quantitatively described and evaluated with the levels explained in Table 3.5: the higher the level, the greater the ability to deliver (advanced) grid services by a PV system:

- **Level 1** indicates a barrier to deliver ancillary services with solar PV or does not have a (positive) impact on the delivery of grid services.
- **Level 2** indicates an incentive to provide ancillary services with solar PV, however the solar PV installation cannot be used optimally or is partially limited to the delivery of simple ancillary services or certain types of solar PV installations.
- **Level 3** indicates that PV installations are enabled to deliver (advanced) ancillary services or/and are incentivized to use the PV installation optimally.

In addition, the formulation of the KPIs is based on the technological capability of a PV system to provide grid services, such as inverter controllability and forecast accuracy, as well as the applicable legislation and regulatory framework. Section 4 will elaborate further on the different kinds of ancillary services and the regulatory framework of the grid services in the European Member States applied to PV systems. Readers with no experience in ancillary services are recommended to read first Section 4.3 before diving into the description of the KPIs.

Although these KPIs have separately a direct impact on the ability to provide ancillary services by PV systems, some KPIs will indirectly have an effect on other KPIs. Where the availability of live data would enable a PV system operator to offer his power as a grid service, it would also impact the forecast accuracy of the PV plant's production. The same is valid for the impact of the auction horizon on this forecast accuracy. Also, the possibility to provide a market-based grid service, will be affected by the auction resolution.

The KPIs mentioned in this Section can serve as a quality measure for regulatory market design for policy makers and as reference documentation of ancillary services for grid service providers, such as aggregators.

Table 3.5: Overview of new grid service KPIs. Each KPI indicate the ability of a solar PV system to perform or deliver ancillary services (source: own analysis)

KPIs	Level 1	Level 2	Level 3
Possibility to control power output	No	Yes, local control or remote control with reaction time between 3’ - 1’	Yes, remote control with reaction time < = 1’
Obligation to participate in system services with PV	No	Yes, with restriction of market-based system services	Yes
Possibility to participate in market-based system services with PV	No	Yes, PV is not treated non-discriminatory (negatively)	Yes, PV is treated non-discriminatory or treated beneficial compared to other technologies
Availability live data	No	Yes, with temporal resolution between 15’, with delay between 15’-1’	Yes, with temporal resolution < = 1’, with delay < =1’
Voltage level grid support	No grid support by PV	Grid support from PV systems connected to TSO level	Grid support from PV systems connected to TSO and DSO level (LV included)
The auction horizon	horizon > week	W-1 >= horizon > D-1	Horizon <= D-1
The auction period	resolution > 12 hours	12 hours <= resolution < 1 hours	resolution <= 1 hours
Presence of local irradiance sensor	No local irradiance sensor present	Local irradiance sensor not on site, but installed near the power plant	Local irradiance sensor presents on site
Presence of battery	No	Yes, battery is purely used for on-site optimization	Yes, battery can directly be used for grid services

3.5.1 Interpretation of the KPIs and the influence on the ability to deliver grid services

Possibility to control power output

A basic requirement to provide grid services with solar PV is to have a controllable system. This could be a local control mechanism based on an on-site optimization or a local grid optimization, e.g., based on the voltage of the PCC (Point of Common Coupling) - or being able to be controlled remotely. To provide advanced system services, remote controllability is often a must, since most of them are centrally controlled.

Obligation to participate in system services

Delivery of system services is obligatory for certain production units connected to the grid. These connection requirements are described in the European Network Code on Requirements for Generators (RfG). These requirements were historically determined on a national level, but the European Commission started the process of harmonizing them with the RfG (see Section 4.4). Examples of obligatory system services are voltage control and fault-ride through.

Possibility to participate in market-based system services

Other grid services are organized as a market or auction in which parties can voluntarily participate. Grid operators are often responsible to facilitate these grid services and organize these markets/auctions themselves and/or work together with (European) market platforms. Grid operators oblige participants in these markets to meet certain requirements and follow a prequalification process including simulations or pragmatic testing. The requirements can have a discriminatory character by excluding certain types of technologies, e.g. market entrance is only allowed for large (thermal) power plants or by excluding consumption installations. Technological requirements can also indirectly exclude PV power plants, e.g.: a required availability of 24h that excludes PV because of the inability to produce at night and forecast uncertainties. Examples of market-based grid services are reserve power provision (e.g. FCR, aFRR, mFRR), black start and congestion management.

The auction horizon

The auction horizon or product lead time, i.e. the time between the gate closure time of the auction and the actual delivery period, is a determining factor of the possibility to provide grid services with PV. The larger the auction horizon, the more difficult to have an accurate forecast and the more difficult to estimate the available power for grid services.

The auction resolution

Auctions are organized based on a certain time resolution dividing the delivery time in blocks. This can vary from hourly blocks to daily, weekly or even yearly blocks. The grid service provider has to ensure that the offered volume is available during the whole time period of the block. As a consequence, the duration of such a block will strongly determine the ability of PV to participate in the auctions. Due to the intermittent character of PV, long time blocks will result in lower volumes, since the auctioned volume has to be available over the whole time block. Time blocks that force service providers to be available for a time that include both night-time and day-time hours, will exclude PV entirely. Time blocks that include all daytime hours, limit bidders to the minimal available power over the whole product period. Due to low power output during sunset, sunrise or cloudy periods, this again hinders participation of PV greatly. Therefore, a small auction resolution would enable service providers to offer more volume with PV.

Availability live data

Live data of PV power plants is essential to have a high forecast accuracy, which is often needed to provide (advanced) grid services such as provision of reserve power. It is used to evaluate if and how much system services a solar plant can provide in the next hours or days. The higher the resolution and the lower the delay of the transmission of the live data to the grid service provider, the better the forecast and the better the estimation of the available power to provide grid services. Also, the TSO may demand real-time data to participate in grid services.

Voltage level grid support

Electrical installations, including generating and consuming units, are connected to a certain voltage level in the grid. Depending on this level, technical units, are allowed or obliged to provide grid services to either the TSO or DSO. Currently, installations connected to the TSO-level have in many EU countries more possibilities to provide ancillary services. In order to enable DSO level-connected PV installations to deliver grid services, national regulation of the European Member States should include the possibility of grid service provision from lower voltages levels as well.

Presence of battery

Without a battery, solar PV can deliver downwards reserve power products by curtailing the output power, but the delivery of upwards reserve power is more complicated. To offer also upwards reserve power, the PV power plant should curtail continuously and only increase power injection when it is asked by the grid operator. When a battery is present on site of a PV system installation, it enables the battery-PV system to provide both upward and downward reserve power products without requiring the PV installation to curtail continuously. This also allows to store the energy when downwards reserve power is provided, instead of curtailing it and therefore creating more energy losses. In such a setup, the grid services are thus delivered by the battery and not by the PV directly.

Local irradiance sensor

A local irradiance sensor enables the grid service provider to establish a baseline when power would be curtailed. The baseline which forms a reference for the power that would be injected into the grid is a necessary to determine the actual delivered power. It also enables the procuring party of the grid service, often the grid operator, to control the delivered volume.

Forecast accuracy

A grid service provider uses a forecast to estimate how much volume would be available to offer as a grid service. Based on the accuracy of the forecast, a part of the volume can be offered considering an uncertainty margin. A low forecast accuracy would require a large uncertainty margin to ensure the availability of the offered volume. The increase of the forecast accuracy would reduce the need for a large margin, therefore entailing more volume provided by the PV installation.

3.6 Conclusion

An overview of the European PV fleet capacity was presented, showing the current state of the solar PV production park in each Member State. Germany and Italy had an installed PV capacity at the end of 2019 of respectively 49GW and 21GW, which translates to a share of 22% and 19% of their total national installed production capacity. Moreover, the Netherlands, Belgium and Malta exceeded the 25% share of their total installed production capacity.

Although BAPV and ground mounted installations are widely spread over Europe, BIPV and floating PV systems still represent a very small amount in the current PV landscape.

Not only the incentive of investment in solar PV is strongly affected by the support schemes offered by the government, also the segmentation of PV capacity per sector is influenced by it. This leads in some Member States to the domination of PV in certain sectors. While in Germany the segmentation is more evenly distributed, in Belgium and Austria support schemes were mainly directed towards (residential) rooftop PV, leading to a solar PV park dominated by residential systems.

In addition, an overview of the current support schemes was presented for each Member State. It is clear that FIP schemes are currently very popular in the European Member States. FIT schemes are replaced by FIP or other mechanisms but are still common for small scale PV. In some Member States subsidies are given to a certain sector. Moreover, quota systems, tax reductions or exemptions and soft loans are also used in the European Member State. Subsidies are sometimes granted based on technology (e.g., battery-PV combinations in Germany) or sector (e.g. agriculture sector in Romania).

European Member States make use of a database, usually operated by DSOs and /or TSOs to store valuable information about PV (and storage) systems installed in their grid area. An overview of PV databases was provided based on the PVPS study [3] and surveys and interview with grid operators. When observing the different databases, it is clear that the level of detail of the registration parameters varies a lot between the different Member States. In some Member States, all PV systems are obliged to register their installation, but several countries mentioned databases solely used for certain systems when they want to receive government support or certificates of origin. The latter case leads to uncomplete databases.

Information about PV systems is often not only stored in one national centralized database. Most of the grid operators do not make use of shared database with another party. Several of them indicated that although they have not a shared database, it would be interesting to have one. In several cases, data is shared in an aggregated way or only a part of the data is exchanged without actually sharing the database. Also the exchange of data between grid operators is currently not very effective or not detailed enough, which was mentioned by grid operators in Belgium and Italy. In addition, the accuracy of some databases is sometimes questionable, leading to a lot of space for improvement.

Lastly, new grid service KPIs were presented which indicated the ability to provide ancillary services with a specific PV system. These indicators show the importance of the controllability of inverters, a technology neutral regulatory framework, the availability of live data and an accurate forecast. The KPIs introduced in this Section could provide guidance for the design of new regulatory frameworks and policies and for grid service providers, such as aggregators, to study the basic and advanced requirements to enable PV power systems to deliver ancillary services with a focus on balancing mechanisms.

4 Assessment of regulatory environment related with high-level PV penetration into the grids

4.1 Introduction: how regulation can help the integration of solar PV in European grids

The strong growth of renewable electricity production from solar PV and other technologies starts to challenge the way grid operators manage their grids. Where historically large power plants would produce electricity, which was then transmitted and distributed to load centres, wind and solar parks are dispersed and often located at lower voltage levels, at the end of power lines, and in areas with historically weak grids. Currently, the impact of solar PV on system balancing and maintaining security of supply is still limited in most European Member States (see Section 0). Yet, interviews conducted in the context of this task reveal that several European DSOs and TSOs expect this situation to change in the next 5 to 10 years.

Even though DSOs and TSOs are responsible for safe system operations in their grid, they cannot operate their own power plants, large loads, or energy storage devices to maintain a stable grid frequency and voltage level. This is a result of the liberalized and unbundled nature of the European electricity market. Grid operators, therefore, rely on the procurement of so-called ‘ancillary services’ from market parties to fulfil these tasks. The term ‘Ancillary services’ refers to a wide range of functions, which include balancing reserves, reactive power, and system restoration services after a black-out.

Careful design of the functioning rules of these ancillary services ensure that grid operators have the necessary tools to manage the growth of solar PV and other decentralized sources in their grids. Additionally, the grid connection requirements for solar PV can further dictate how solar assets should behave in moments of large frequency and voltage deviations. This way, an escalation of grid issues is avoided. Careful and future-proof design of such connection requirements ensures that solar PV systems and other type of generators are equipped with the necessary technology to safely operate throughout their lifetime.

Regulation hence plays a pivotal role in the integration of solar PV in Europe. In the sections that follow, the existing regulatory framework and how it accommodates solar PV integration is assessed.

4.2 Technical potential of solar PV for grid support

Before we look at the market design of the different ancillary services and connection requirements in Europe and their openness to solar PV, it is important to consider in which ways solar PV could support grid operations from a technical point of view.

Solar PV parks are connected to the grid through invertors and are therefore able to respond quickly and accurately to set points, which could be sent remotely by a grid operator or a market party like an aggregator or Balancing Service Provider (BSP). Scientific literature and pilot projects suggest that solar PV can participate effectively in a number of services that would support grid operations [20]. They can be divided on two groups, based on the fact that they are either triggered by a certain system state (frequency or voltage level, rate of change of frequency…) or through an external setpoint sent by a grid operator or market party.

Support based on the system state:

- **Inertial response,** either as synthetic inertia or as physical inertia in case the solar asset is connected to a fast energy storage system, such as a supercapacitor. It should be noted that inertial response is not contracted as an ancillary service in Europe today, since it is seen as an inherent property of the synchronous generators (in thermal or hydro power plants). It is therefore not even measured or remunerated.

- **Ramp rate control**, which refers to the active regulation of the power output increase or decrease of the solar PV plant. There is no ancillary service today that procures ramp rate services; conventional power plants are counted upon to match the high ramp rates of renewable power output.
- **Controlled fault behaviour,** when frequencies or voltage levels largely deviate from normal levels, solar PV convertors can respond in a prescribed way to avoid escalation of the issue and contribute to a return to normal values.
- **Voltage support through reactive power provision:** modern solar PV convertors are able to absorb and inject reactive power and as such support stable voltage levels in the grid.

Support based on external triggers from e.g. the grid operator:

- **Curtailment of the power output**, in case of voltage issues or congestion in the grid area to which the solar PV system is connected.
- **Frequency containment reserves,** which is the automatic response to frequency fluctuations in the grid. Since this product is often procured in a symmetric way, permanent curtailment is necessary to foresee 'headroom' that allows an increase of the power output when necessary, if PV wants to offer this service without complementing assets such as loads or batteries.
- **Frequency restoration reserves,** which are activated by TSOs to restore the balance between supply and demand in their control area. Where these reserves are procured symmetrically, 'headroom' needs to be foreseen. Since activation of restoration reserves can last over several quarter hours to multiple hours, the reliability of its provision by solar PV can be increased by coupling it to a battery energy storage system (BESS).

There are two important elements to consider when investigating the possibility of using solar PV for grid support:

- The provision of services listed above can only happen during moments when the solar resource is available, i.e. during daytime. The availability of the service is weather-dependent and difficult to forecast long in advance, which is a major barrier for its participation in existing ancillary services. This will be discussed in more detail in the next sections.
- The provision of the services listed above requires a fundamental shift in the operation of a solar plant: from 'basic solar' which simply produces based on the available solar resource, to 'dispatchable solar' of which the power output is controlled based on the conditions in the grid or an external setpoint.

In Europe, a number of grid support services are already required from (newly built) solar PV assets in the grid connection requirements. Such services are expected to be delivered by the solar PV asset at all times and are not remunerated – even though some of them impact the injected active power and hence the income of the solar plant. We therefore study these grid connection requirements in detail in Section 4.4. Services related to frequency support are organized in a separate manner in the so-called balancing power products. As we will discuss in Section 4.5, solar PV does not yet participate in these balancing products in Europe today.

Section 4.3 defines the different ancillary services in Europe a detailed way. Readers experienced in this matter can skip this part.

4.3 Common ancillary services in Europe

Ancillary services are an indispensable tool of grid operators, who are responsible for a safe operation of their distribution or transmission grid. The term “ancillary services” refers to a wide range of functions, that can be grouped in four categories:

- **Frequency support**:
  - Goal: To avoid black-outs and maintain a stable frequency of 50 Hz, needed to avoid damage to (or tripping of) grid connected equipment (from power plants to household appliances).
  - On the one hand, grid operators contract balancing energy from market parties, which allows to modulate the power generation or demand to balance supply and demand.
  - On the other hand, connection requirements for grid connected assets, including solar PV, can prescribe how assets should behave to avoid escalation during large frequency issues frequency deviations.
- **Voltage support**:
  - Goal: For safe system operations, the voltage levels in the grid should not deviate more than 10% from their nominal value.
  - Grid operators demand or contract provision of reactive power or active power modulation to restore voltage levels. Connection requirements describe how assets should behave to avoid escalation during large voltage issues.
- **Congestion management**:
  - Goal: relieving lines or other grid components which are threatened to be overloaded.
  - Grid operators demand or auction the rescheduling of production or demand to relief the congested grid area.
- **System restoration**:
  - Goal: restart the grid after a black-out.
  - Bringing power back in a synchronous grid is not straightforward. Ancillary services like black start allow grid operators to power up power plants and reconnect load centres in an organized manner, to gradually restore safe operation of the grid.

Not all European grid operators procure these ancillary services in the same way. As becomes apparent from the overview above, ancillary services can either be demanded from (generation) assets in the grid connection requirements, or they can be procured via separate mechanisms, such as auctions. This is especially the case for the group of services related to system balancing for frequency support. We therefore first treat the regulatory framework around the grid connection requirements in Section 4.4 and then the regulatory framework around system balancing in Section 4.5.

4.4 Connection Requirements for Generators

To integrate new elements in the grid, it is important that they fulfil certain technical requirements. These are put forward to ensure the new grid element would not have a negative impact on the safe operation of the grid. Usually, different grid connection requirements exist for demand and generation, and further depend on the voltage level the asset is connected to and the assets’ size.

Historically, Member States developed grid connection requirements independently. With the rise of intermittent power generation, the number and variety of connection requirements for generation assets kept growing. To ensure a well-functioning market for (renewable) generation technology and a level-playing field in the context of the European Energy Union, the European Commission saw the need to harmonize the connection requirements in the European rules. In 2016, the Network Code on Requirement for Generators

(RfG NC)(Commission Regulation (EU) 2016/631)[4] was put in place, which provides a harmonized framework for connection requirements for generators in Europe. Separate connection codes for demand and DC-grid connected assets were adopted in the same year.

In this Section, we will focus on the RfG NC (further shortened to 'the RfG') since it is most relevant to solar PV. The local implementation of the RfG took place in the years following 2016 and is now implemented in all member states, as shown in the figure below from the ENTSO-E.

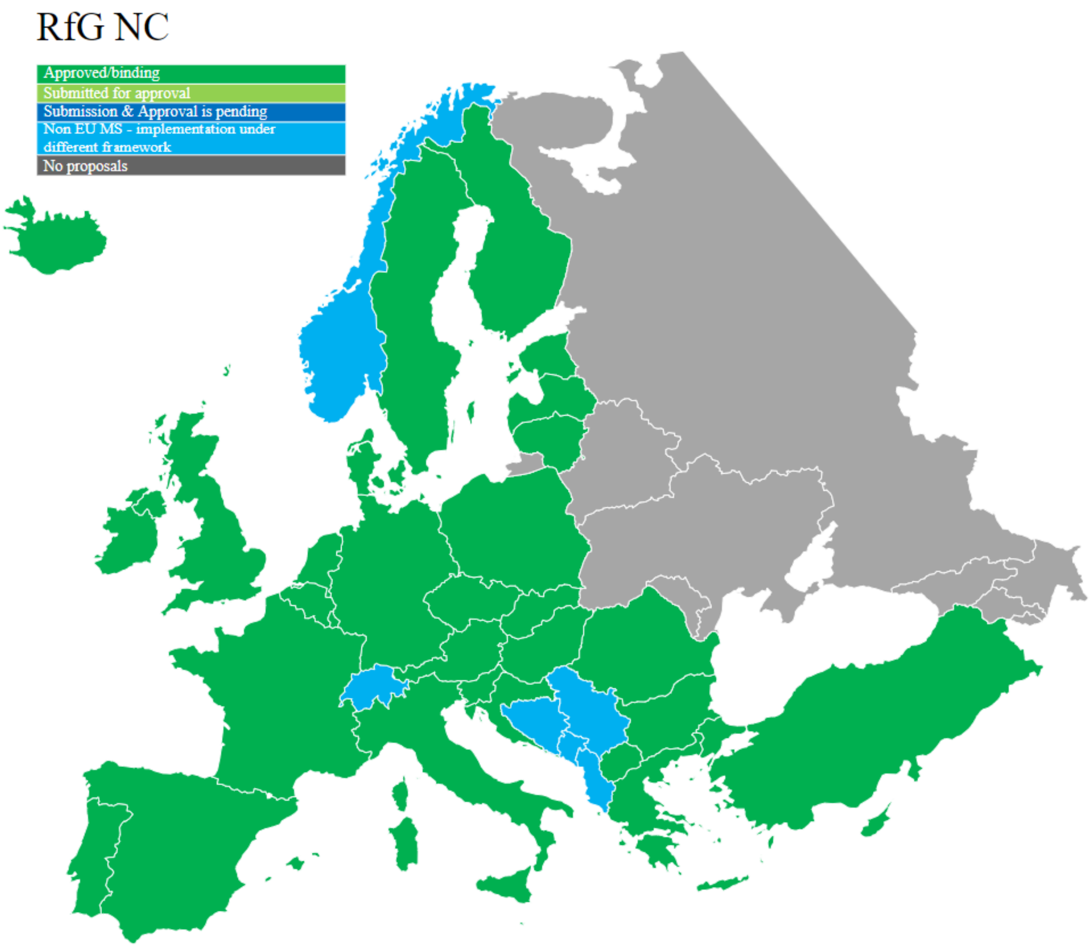

Figure 4.1 : Overview of the status of the implementation of the NC RfG in European Member States (source: [5])

4.4.1 Main elements of the Network Code on Connection Requirements for Generators

4.4.1.1 Type of generation asset

The RfG connection standards apply to all new power-generating modules built after the local implementation of the RfG. It applies to all power generating technologies, including solar PV and certain types of pumped hydro storage. Cogeneration assets (CHPs) are relieved from certain provisions. The RfG does not apply to energy storage systems by default, but some Member States have chosen to treat energy storage as a generation technology, hence falling under the RfG.

The RfG distinguishes between three categories of power generating modules:

- **Synchronous Power Generating Module (further abbreviated as SPGM)**: an indivisible set of installations which can generate electrical energy such that the frequency of the generated voltage, the generator speed and the frequency of network voltage are in a constant ratio and thus in synchronism. In practice, this category contains all technologies that generate power by driving an alternator, such as nuclear, coal, gas, and hydro plants.
- **Power Park Module (further abbreviated as PPM)**: a unit or ensemble of units generating electricity, which is either non-synchronously connected to the network or connected through power electronics. This category covers renewable energy technologies like solar PV and wind.
- **Offshore Power Park Modules**: a power park module located offshore with an offshore connection point. This could be an offshore wind park, for example.

4.4.1.2 *Type of significance*

Generators need to comply with a defined set of requirements, which depends on the voltage level of their connection point and their nominal capacity. These two parameters determine the significance of the generator in the context of grid operations; the fewer impact a generator has, the less stringent the requirements. The RfG therefore introduces four generation categories, called Type A to Type D. Type A assets are the smallest and are located at the lowest voltage ranges of the grid. An individual Type A asset has therefore little impact on grid security and have to fulfil the least stringent requirements. Type B assets are somewhat larger assets in the low and medium voltage grid. They, too, are considered to have limited significance for grid security. The requirements for Type A and B assets are mostly limited to withstand disturbances in the grid without disconnecting or responding in a way that would make the underlying issue worse. Types C and D are larger assets connected to the medium and high voltage grid that have an immediate impact on system security and therefore have to fulfil several additional requirements, such as providing balancing power and black start services.

The RfG sets out the capacity thresholds for each type, depending on the synchronous area (see Figure 4.2).

Synchronous areas	Limit for maximum capacity threshold from which a power-generating module is of type B	Limit for maximum capacity threshold from which a power-generating module is of type C	Limit for maximum capacity threshold from which a power-generating module is of type D
Continental Europe	1 MW	50 MW	75 MW
Great Britain	1 MW	50 MW	75 MW
Nordic	1,5 MW	10 MW	30 MW
Ireland and Northern Ireland	0,1 MW	5 MW	10 MW
Baltic	0,5 MW	10 MW	15 MW

Figure 4.2 : Overview of default thresholds for Type B to Type D assets for the different European synchronous areas (source: [4])

Regulators can deviate from these if it is deemed desirable in the local context. Germany, for example, with its large number of solar assets between 100 kW and 1 MW, decided to lower the threshold for type B assets to 135 kW. As a result, these assets need to fulfill more requirements than systems of the same size in for example France (which uses the default threshold of the RfG of 1 MW). Countries like Sweden decided to increase the threshold for type B assets to 2 MW, higher than the default of 1,5 MW for the Nordic synchronous area. The large variety of thresholds is also a result of existing national connection requirements that were in place before the adoption of the RfG. Most member states tried to fit existing requirements into the RfG framework when it had to translated into national grid codes.

An overview of the current thresholds of a selection of member states is shown in Figure 4.3. These thresholds can be updated by the relevant regulatory body every 3 years.

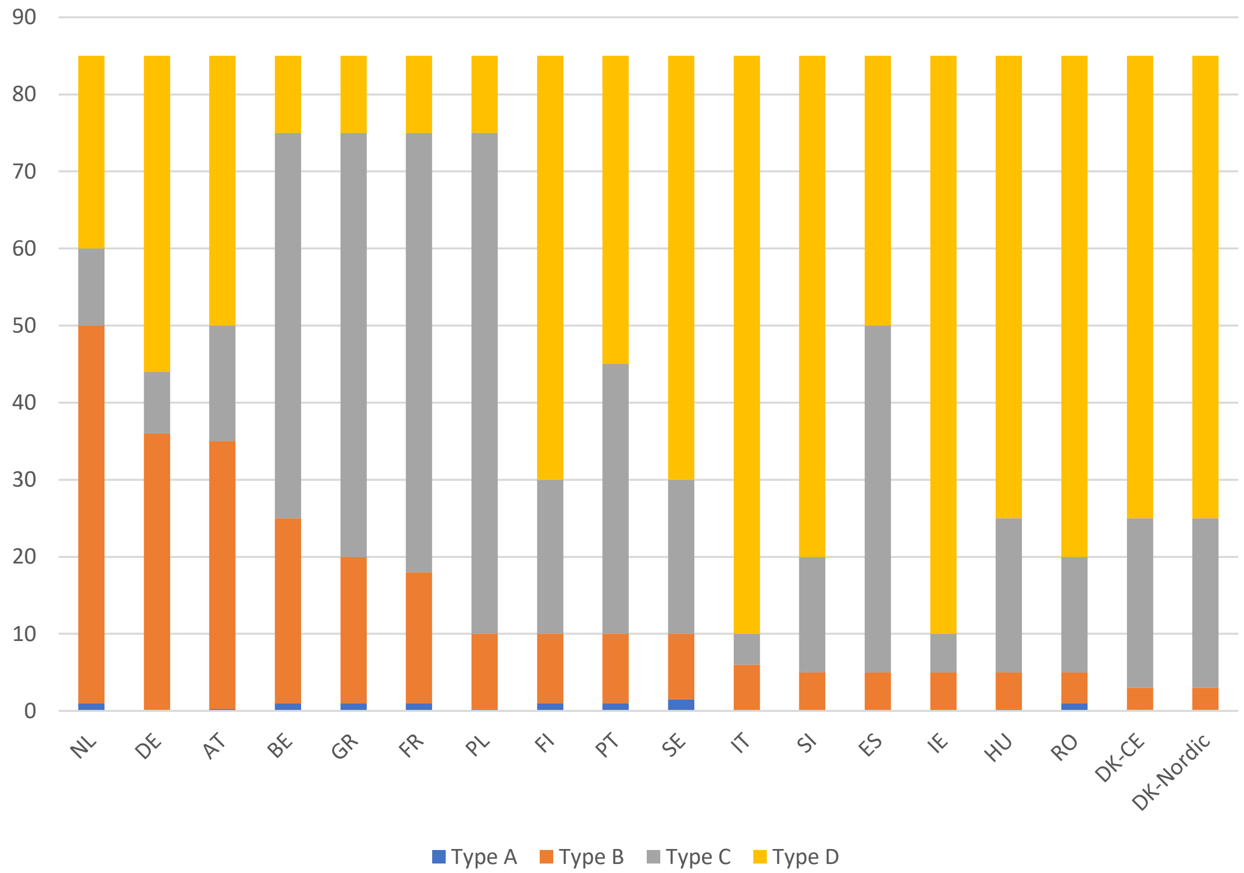

Figure 4.3 : National thresholds for Type A to Type D assets in the framework of the RfG (source: own analysis)

4.4.1.3 Categories of Requirements

The requirements listed in the RfG can be roughly categorized in three groups, depending on the type of system issue they address:

- **Ensuring a stable frequency**: these requirements define how generators should behave in different frequency ranges, to ensure that system frequency is maintained at 50 Hz, and that large frequency deviations do not lead to large-scale disconnection of generators, which would aggravate the situation.
- **Voltage support**: these requirements describe how generators should behave in different voltage ranges, and to ensure over- and undervoltages are avoided as much as possible. They also define how generators should respond in cases of large voltage fluctuations.
- **System restoration**: these requirements define how generators should behave after a black-out, and how they need to help grid operators to restart the grid.

4.4.2 Overview of selected requirements

The RfG contains a large number of requirements, which often have several specifications for related technical parameters. In total, more than 200 parameters are defined. It is outside the scope of this task to list them all. In the Table 4.1, we have selected the most important requirements for generators. They are also illustrative of the differentiation between Type A-D assets, and the different categories of power generating modules.

In Table 4.2, the applicability of these selected requirements to the different asset types and categories is shown. For clarity's sake, we did not list applicability to offshore power generating modules since this is less relevant for solar PV.

The first four requirements relate to the required behaviour of generators in case of frequency deviations outside a certain band around 50 Hz (defined by the relevant grid operator). These requirements ensure that issues in the system frequency are not aggravated by the automatic and sudden disconnection of generators at the same time. Since these requirements are fundamental to avoid runaway frequency deviations, they apply to all types and categories of generators.

The next requirements relate to active power control to restore the frequency. Assets of Type A only need to be able to be shut off entirely, and grid operators have the option to make this function remotely controllable. Assets of type B need to be able to not just shut down, but to have a more precise active power control. The grid operator can again choose to make remote controllability obligatory. Assets of type C and D need to fulfil stricter requirements: they are obliged to participate in FCR and aFRR services according to the local rules. In countries where such services are entirely voluntary, the obligation will de facto not apply.

Most frequency related connection requirements are applicable to both power park modules and synchronous power generating modules. An exception is the provision of synthetic inertia, which applies to PPMs to mimic the behaviour of synchronous power generating modules during fast frequency deviations.

The next group of requirements relates to voltage issues, which could both be under- or overvoltages. Type A assets do not need to fulfil the most important voltage related requirements, while all other types usually do. The requirement to be able to withstand voltage faults and stay connected to the grid is only required for SPGMs, while the ability to control the active power to influence the voltage level is obligatory for both PPMs and SPGMs of Type C and higher. Provision of reactive power is not obligatory by default in the RfG but can be made obligatory by the grid operator if deemed desirable, for SPGMs, PPMs, or both.

The last group of selected requirements refers to system restoration after a black out. To restart the grid, power plants need to be able to inject into the grid in the absence of a system frequency. This is called black start. These services are not obligatory by default but can be made so by grid operators. In any case, they only can be required from Type C and D assets. Active power recovery refers to the ability to start injecting again as soon as power is brought back. This is required only from SPGMs from Type B and higher. Reconnection to the grid after an automatic disconnection due to a system fault is obligatory for all categories of generators from type B upwards.

Table 4.1: Overview of a selection of important requirements from the RfG (source: own analysis)

	Requirement	Article RfG	(Partially) Optional	Explanation
Frequency Issues	Frequency range	13.1.a.(i)		Continue normal operation within given frequency band for a minimum given time
	Rate of Change of Frequency (RoCoF)	13.1.b		Continue normal operation below a maximum Rate of Change of the Frequency (RoCoF)
	LFSM-O	13.2.a	X	Prescribed frequency response (droop control) during over-frequencies
	Admissible power reduction	13.4-5		Envelope for allowed power output reduction when frequencies drop below threshold
	Remote curtailment through logic interface	13.6	X	Requirement to have logic interface so that power can be curtailed to 0 within 5 seconds, grid operator has option to make this interface remotely controllable
	Remote active power control through logic interface	14.2.a-b	X	Requirement to have logic interface so that active power can be controlled via the input port, grid operator has the option to require it to be controlled remotely
	LFSM-U	15.2.c		Prescribed frequency response (droop control) during under-frequencies
	Frequency Sensitive Mode (FSM)	15.2.d.(i)		Obligatory provision of frequency response at normal frequency deviations (FCR), according to local rules
	Frequency Restoration Control	15.2.e		Obligatory provision of aFRR or mFRR during large system imbalances, according to local rules
	Real-Time Monitoring of FSM	15.2.g		Transfer of real-time signals to report FCR response to grid operator
	Rates of Change of Active Power Output	15.6.e		Limitations in the ramp up and ramp down speeds of the generator
	Synthetic inertia	21.2	X	Definition of operating principles and performance requirements to provide synthetic inertia during very fast frequency deviations
Voltage Issues	Fault-ride through	14.3.a-b & 16.3.a.(i)		Requirement to withstand faults according to specified voltage-against-time profile
	Active power controllability	15.2.a		Requirement to be able to adjust power setpoint in line with instruction by the grid operator, in order to influence under- or overvoltages
	Reactive power provision	17.2.a & 20.2.a	X	Grid operator has the option to require the capability to supply or absorb reactive power
	Reactive power mode PPM	21.3.d.(vii)		Definition of the reactive power mode to be used
	Reactive Power PPM below Max	21.3.b-c		Definition of required reactive power provision in the form of U-Q/Pmax curve at and P-Q/Pmax below maximum power
System Restoration Issues	Reconnection capability	14.4.a-b		Requirement to be able to reconnect to the network after an incidental disconnection caused by a network disturbance
	Black start capability	15.5.a	X	Grid operator has the option to require generators to provide blackstart services in case of black-outs
	Active power recovery	17.3		Requirement to provide post-fault active power recovery of prescribed magnitude and timing

Table 4.2: Overview of the applicability of the selected requirements to different generator types (source: own analysis)

	Requirement	RfG Article	Type (●=SPGM, ♦ =PPM)			
			A	B	C	D
Frequency Issues	Frequency range	13.1.a.(i)	●♦	●♦	●♦	●♦
	Rate of Change of Frequency (RoCoF)	13.1.b	●♦	●♦	●♦	●♦
	LFSM-O	13.2.a	●♦	●♦	●♦	●♦
	Admissible power reduction	13.4-5	●♦	●♦	●♦	●♦
	Remote curtailment through logic interface	13.6	●♦	●♦		
	Remote active power control through logic interface	14.2.a-b		●♦		
	LFSM-U	15.2.c			●♦	●♦
	Frequency Sensitive Mode (FSM)	15.2.d.(i)			●♦	●♦
	Frequency Restoration Control	15.2.e			●♦	●♦
	Real-Time Monitoring of FSM	15.2.g			●♦	●♦
	Rates of Change of Active Power Output	15.6.e			●♦	●♦
	Synthetic inertia	21.2			♦	♦
Voltage Issues	Fault-ride through	14.3.a-b & 16.3.b.(i)		●	●	●
	Active power controllability	15.2.a			●♦	●♦
	Reactive power	17.2.a & 20.2.a		●♦	●♦	●♦
	Reactive power mode PPM	21.3.d.(vii)		♦	♦	♦
	Reactive Power PPM below Max	21.3.b-c			♦	♦
System Restoration Issues	Reconnection capability	14.4.a-b		●♦	●♦	●♦
	Black start capability	15.5.a			●♦	●♦
	Active power recovery	17.3		●	●	●

4.4.3 Requirements for solar PV

Solar PV parks fall under the rules for PPMs. The most important requirements for PPMs introduced in the previous Sections are summarized below.

Obligatory in all member states:

- All solar PV installations need to fulfil several requirements to withstand large frequency deviations.
- Solar parks of Type C and D need to be able to respond to grid operators' requests to adapt the active power in case of voltage issues.
- Solar parks of Type B and higher need to be able to reconnect after an automatic disconnection in case of a black-out.

Requirements that can be made obligatory if the relevant grid operator chooses to:

- Grid operators have the option to make remote controllability for switching off solar plants of Type A obligatory.
- Grid operators have the option to make remote controllability for active power control of solar plants obligatory for Type B plants.
- Solar parks of Type C and D can be obliged to provide synthetic inertia (in that case, headroom would need to be maintained).
- Reactive power provision can be made obligatory by grid operators for Type B plants and higher.
- Grid operators can demand black start provision by solar parks of Type C and D.

In Table 4.3, an overview is given on national choices on these optional requirements for a selection of Member States. Provision of FCR, aFRR, and mFRR can be made obligatory for solar parks of Type C and D in the national functioning rules of these products. These requirements are discussed in more details in the following Section on balancing power.

Table 4.3: Overview of national choices on selected optional requirements of the RfG (source: own analysis)

Country	Remote curtailment through logic interface	Remote active power control through logic interface	Synthetic inertia	Reactive power	Blackstart
AT	obligation determined per site	obligation determined per site	not implemented	required	obligation determined per site
BE	not required	not required	not required	required	not required
DE	remote control required (radio ripple)	remote control required (radio ripple)	not required	required, specifics per site	obligation determined per site
DK-CE	not required	required	not required	required, only for PPM and only to supply not absorb	not required, market based
DK-Nordic	not required	required	not required	required, only for PPM and only to supply not absorb	not required, market based
ES	not required	not required	required	required	required, not compensated
FI	Not known	Not known	Not known	Not known	Not known
FR	Not known	Not known	not required	required	required
GR	obligation determined per site	obligation determined per site	not required	required, specifics per site	required, specifics per site
HU	required	site specific	not required	required, specifics per site	required, only for for SPGM > 500 MW
IE	not required	required for >1MW	obligation determined per site, market based	required, only for PPM	obligation determined per site, market based
IT	obligation determined per site	obligation determined per site	required	required, specifics per site in case of SPGM	required, specifics per site

Country	Remote curtailment through logic interface	Remote active power control through logic interface	Synthetic inertia	Reactive power	Blackstart
NL	not required	not required	not required	required	obligation determined per site
PL	required, specifics per site	required, specifics per site	not required	required	obligation determined per site
PT	obligation determined per site	obligation determined per site	required, specifics per site	required	required, specifics per site
RO	obligation determined per site	obligation determined per site	required	required	required
SE	not required	not required	not required, market based	obligation determined per site	obligation determined per site
SI	obligation determined per site	obligation determined per site	not required	required	required, not compensated

4.5 Balancing power

One subset of ancillary services is especially important in the day-to-day operations of a grid: balancing power. This refers to the practice of ramping generation assets and demand assets up and down to re-establish a balance between demand and supply in the grid, to restore the frequency to its desired level of 50 Hz. This allows the grid operator to intervene in case a shortage or excess of power develops in his grid, which risks triggering a blackout. To ensure the availability of balancing power, grid operators contract this power in advance. The selected providers are obliged to keep this power available, to be able to respond to a request of the grid operator when needed. Therefore, balancing power is also often called reserve power.

There are two prevailing approaches in Europe in which grid operators allocate and reserve balancing power at power plants (and, in some countries, loads):

- Central dispatch (least common): The grid operator is in full control of scheduling dispatchable power plants and large loads. He allocates certain plants for balancing, taking into account e.g. grid constraints and possibilities for redispatch, etc. based on an integrated planning approach.
- Self-dispatch by scheduling agent or BRP (most common): In this approach, market parties operate their power plants and loads based on their deals on the power exchanges. The procurement of balancing power happens in a separate process, typically an auction organized by the grid operator.

An overview of the approach followed in different member states is shown in Figure 4.4.

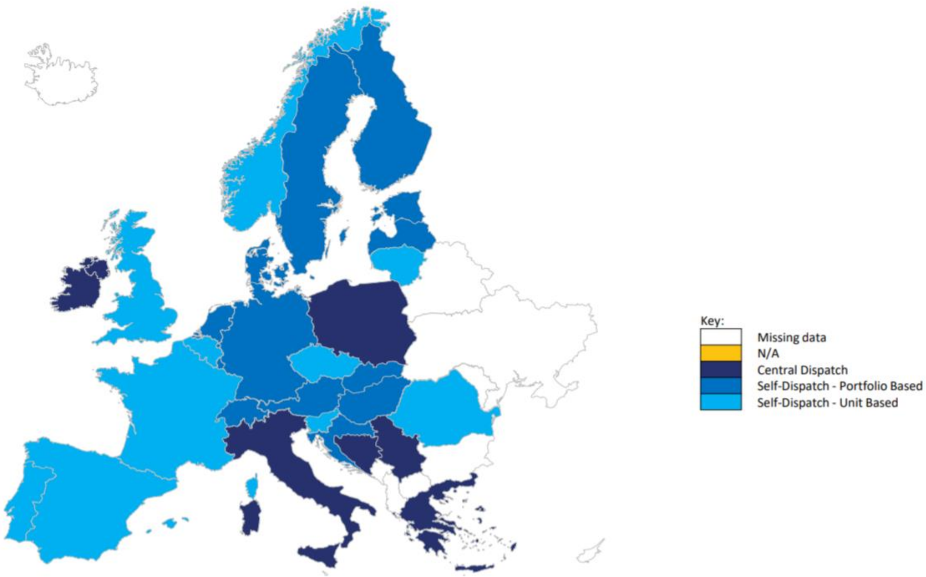

Figure 4.4 : Overview of the prevailing balancing approach in different Member States (Source:[7])

Grid operators define different balancing power products, which are meant to fulfill balancing on different time horizons. The way in which these products are defined and how they are procured differs greatly from country to country. This also means that the possibility to participate in such products with a solar PV asset differs a lot from country to country. In this Section, we aim to give a high-level overview of balancing power products in Europe and provide a closer look at the participation of solar PV power in them.

4.5.1 Most common balancing power products

The ENTSO-E defines four main balancing products which are found in most European countries to a certain degree of similarity. They all play a different role in supporting a stable frequency:

- FCR (Frequency Containment Reserves): continuously monitors the frequency in the grid and will counteract any deviation from the reference frequency (50 Hz). The aim is to limit the frequency deviations in the synchronous grid, so that a collapse (black out) of the system is prevented.
- aFRR (automatic Frequency Restoration Reserves): it is controlled centrally by the TSO of the control area where an imbalance arose. It is activated automatically by the SCADA system of the TSO and needs to be able to be fully activated within less than 15 minutes. After activation, the system operator sends a new setpoint, which must be followed within a strict accuracy band. This enables the grid operator to adjust the balance in a precise manner.
- mFRR (manual Frequency Restoration Reserves): tertiary reserve is used to make the aFRR available again in case of large and prolonged imbalances and must be able to be fully activated within 15 minutes. In case of large imbalances, these reserves can support the frequency for minutes to hours.
- RR (Replacement Reserves): an additional reserve product that is being used to free up assets providing aFRR and mFRR, so that they become available to compensate for additional system imbalances.

These four balancing products are schematically illustrated in Figure 4.5.

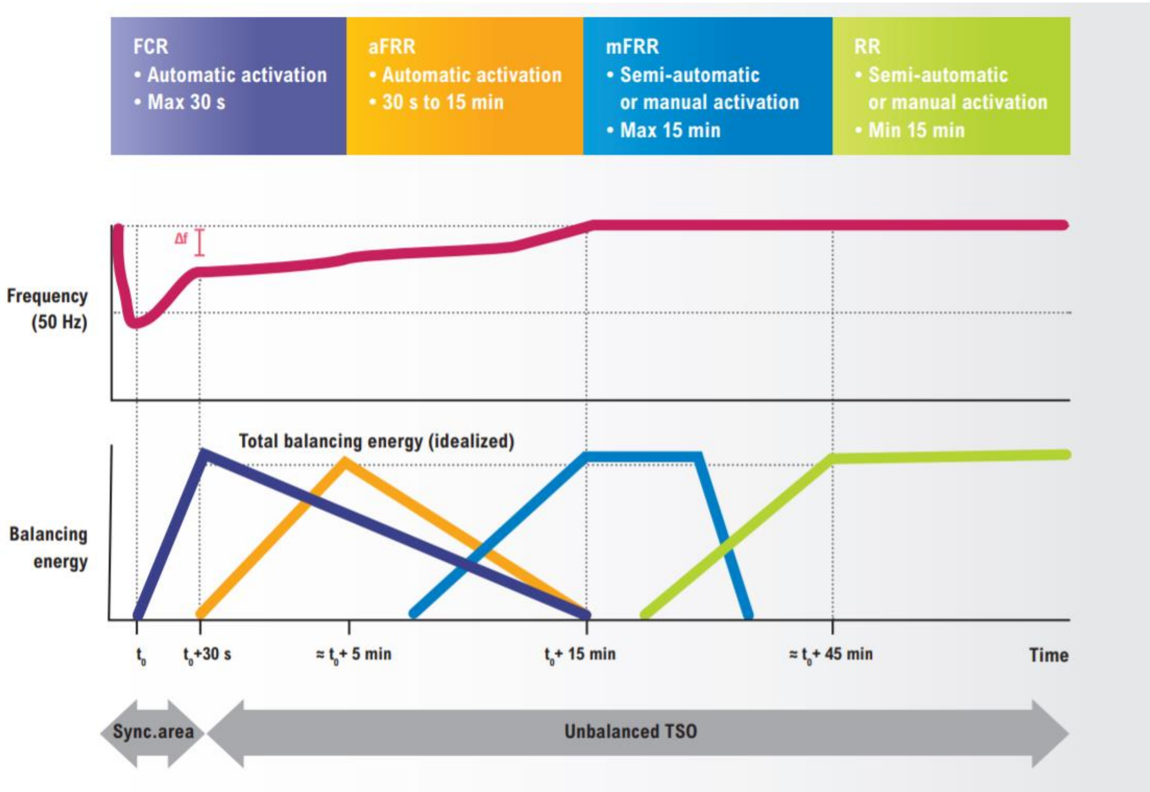

Figure 4.5 : A schematic overview of the common European balancing power products (source: [6])

4.5.2 Most important characteristics of a balancing power product

Even though the balancing products in different Member States usually fit in the product categories defined by the ENTSO-E listed in the previous Section, the differences are big. The most important characteristics of a balancing product are as follows:

- **Market access**, i.e. who can participate:
    - market based or obligatory service;
    - minimum installed power to participate;
    - voltage levels from which one can participate;
    - technologies that can participate.
- **Remuneration scheme** for the service:
    - No remuneration, regulated fee, or market-based remuneration (which can be marginal pricing or pay-as bid).
- **Contract period**:
    - 1 year, 1 month, 1 day, 4-hours, 15 minutes, …
- **Lead time of the auction**:
    - Before the start of the contract period the auction is organized 1 year, 1 month, 1 week, 1 day…
- **Product symmetry**:
    - Symmetric product requires modulation of power up and down.
    - Asymmetric product requires modulation of power in one direction only.
- **Possibility to offer 'free bids'**:

    - Ability to offer flexible power on short notice, which can be 15 minutes, 30 minutes, 1 hour,… This power is not contracted and thus not reserved by TSO beforehand.
- **Requirements for real-time and ex-post data exchange** between the reserve providing asset and the grid operator:
    - Data resolution and latency requirements
    - Data communication channels: leased line, dedicated communication infrastructure of the grid operator, etc.
- **Acceptance test**:
    - Requirement to clear an acceptance test before an asset can participate.
- **Penalties**:
    - If and how assets are penalized if they do not provide the balancing power to the extent or the duration as requested by the grid operator.
- **Baseline methodology**:
    - The methodology used to determine how much power the reserve providing asset would have produced or consumed if balancing power would not have been activated by the grid operator. This immediately determines the remuneration and penalty settlements.

4.5.3 Participation of solar PV in balancing power

Historically, balancing power has been provided by large-scale dispatchable power plants and large loads, such as industrial plants. Smaller-scale or intermittent generation and difficult-to-predict demand have historically been excluded from the balancing power markets, because of the need to reserve flexible power in advance, which can be called upon when the grid operator needs it.

In a search for more cost-effective procurement of balancing power, several Member States have started opening their products and markets to a wider variety of technologies and asset sizes, working towards technology neutral participation requirements. This market driven approach is also reflected in the adoption of the Electricity Balancing Guideline at the European level (COMMISSION REGULATION (EU) 2017/2195) [21]. In countries like Germany, the opening of the balancing markets has brought down the prices tremendously over the last decade [22]. This results in lower balancing costs for grid operators and eventually smaller grid fees for consumers.

Synchronous generators, renewable technologies like biogas motors and (pumped) hydro installations have been successfully participating in these products for several years, if allowed by the regulatory framework. A number of TSOs have tested delivery of the aFRR-product with wind power too, such as Belgian TSO Elia [23]. Solar, on the other hand, experiences difficulties to participate in the current European balancing markets.

In the following sections, we investigate the reasons behind this difficulty to participate in the balancing products and the ongoing harmonization of these products on a European level.

4.5.3.1 Common barriers for solar PV to participate in balancing power

The regulatory framework for balancing products is still strongly influenced by their historical origins, when large conventional power plants exclusively provided these services. For example, grid operators are used to contract balancing power in advance. This way, sufficient available balancing power is ensured at any time. Conventional power plants contracted for the service can reserve a band for balancing in their operational schedules. Measurements and quantification of the delivered balancing power are also straightforward with large power plants: one can simply take the operational schedule as the reference or baseline.

In an attempt to open balancing products to decentralized assets like biogas motors, emergency gensets, and demand response, some European grid operators have reformed the balancing products to be more accessible. Still, there are many barriers for solar PV to participate. They can be divided into three groups:

- **Lack of technology neutrality or market access**:
  - Either a complete exclusion from delivering the service, independent from system size or voltage level, or;
  - Exclusion from provision of balancing with assets in the distribution grid, where most solar PV is connected. This is the case in Italy, for example.
- **Long contract periods and lead times:**
  - If the contract period requires the balancing power to be available during night times, solar PV cannot participate.
  - If the auction for the balancing product takes place more than 24 hours before the start of the delivery period, it is very difficult to commit a certain amount of flexible power for balancing. The risk that unforeseen weather changes impact the availability of the power reserved for balancing is too big, they would result in penalties and eventually an exclusion of the asset from the service.
  - Balancing products that have the option to only offer in the energy auction (also known as 'free bids' or 'bidladder'), which usually have lead times up to less than 1 hour before delivery time, are more accessible to solar, since the flexibility does not need to be reserved long in advance. That way, the issue of long lead times or contract periods is circumvented. Lack of such free bids limits participation of solar where contract periods and lead times are long.
- **Lack of measurement and quantification standards:**
  - The provision of balancing power is usually determined by comparing the actual power output with its so-called baseline or reference power. A baseline methodology that is not adapted for intermittent resources hinders participation of solar PV.

Even though solar PV is technically able to provide balancing in two directions if it foresees 'headroom', it usually creates a large opportunity cost. Therefore, the symmetry of balancing products also immediately impacts the participation of solar PV:

- **Product symmetry**: The balancing product is symmetrical, which requires to ramp the power output up and down. Without the combination with battery energy storage, this would mean that the solar plant needs to curtail power permanently to foresee 'headroom' to provide upward balancing energy. That is usually not economically feasible, given the loss of subsidies.

It is clear that a regulatory environment in which these barriers are reduced or taken away entirely, opens the door for participation of solar PV in system balancing. The ongoing European harmonization projects (see further) are already addressing the issues of technology neutrality and market access. More work has to be done with respect to the contract periods, lead times, and symmetry requirements. The current state of these characteristics is listed for a selection of Member States in Section 4.5.3.2. At the moment of writing, no Member State has an adequate baseline methodology for participation solar PV in balancing. In the interviews organized with several European grid operators, it became clear that not much progress has been made to overcome this barrier.

Two more indirect barriers for participation of solar PV in balancing are worth mentioning:

- Certain support schemes for renewables create a disincentive for solar PV to participate actively to system balancing, such as feed-in tariffs and priority injection rules.

- There is a lack of regulation around the coordination of ancillary service procurement between TSOs and DSOs. This lack of communication between grid operators is long recognized, yet the grid operators interviewed in the context of this study indicated that little progress has been made.

4.5.3.2 Evaluation of solar PV participation in European balancing products

Evaluating where solar can definitely participate in balancing, and where it can definitely not, has proven difficult. The authors did not find regulation that explicitly forbids solar PV from participating in balancing power, but in most Member States the requirements make it very hard if not impossible to participate in practice. As many European grid operators were contacted as possible, but limited response was received within the timeframe of this subtask. The regulatory texts are therefore the main source for the analysis.

First of all, we see distinction between countries with a central dispatch approach versus countries with self-dispatch. Where central dispatch is applied, grid operators already actively control the power output of variable renewables. In most cases, this is primarily with wind power and to a lesser extent solar. Some examples:

- **Spain**: already in 2006, Spanish TSO Red Eléctrica de España (REE) launched the Cecre control centre for renewable energies [24]. All renewable generation units larger than 5 MW are connected to this national control centre, providing live data every 12 seconds. This information is processed, analysed, and exchanged with the REE Grid Control Centre. When necessary, curtailment of renewables can be triggered, which need to be answered within 15 minutes. Even though most information available focuses on wind power, we did not find information that indicates that solar PV is excluded from this. As prescribed in the Connection Requirements, FCR needs to be provided from generators of type C and higher, while aFRR and mFRR participation is voluntary. Since FCR is only procured as symmetric product, it can be concluded this does not need to be delivered by solar PV.
- **Greece**: Greek TSO IPTO requires type C and D generators, including solar, to provide FCR, aFRR and mFRR. FCR does not need to be provided in a symmetric way, allowing renewables to offer this service more easily. Bids need to be made the day before dispatching day, so two days before delivery. Special rules for renewable balancing service providers were adopted, among which the obligation to immediately inform the TSO in case the outlook on available balancing power has changed after the bidding has ended, which takes place two days in advance [25].
- **Poland:** Even though the connection requirements prescribe all generators, including solar, to provide FCR, aFRR, mFRR from type C upwards, own experience from the consortium partners learns that solar PV cannot participate yet in balancing. FCR is procured in a symmetric way, while aFRR is procured asymmetrically.
- **Italy:** *Company J* (Italian grid operator) already control the output of solar and wind parks as part of redispatch. Solar PV cannot yet participate in balancing products like FCR or aFRR. These products are still very much designed for dispatchable large power plants, although *Company J* has launched the UVAM pilot project to start procuring balancing from smaller scale (demand response) assets. Due to the fact that the operational schedule is used as baseline, this remains difficult for variable renewables like solar PV.

Member States with self-dispatch models, usually employ a more market-based approach in balancing. We did not find that any of the member states explicitly excludes solar PV from participating. In all countries, with and without central dispatch, type C and D assets, including solar, are in fact obliged to participate. The product duration, lead time, and symmetry then determine whether it is de facto doable for solar PV to do so.

The product symmetry, contract period, and lead times were investigated for a selection of European member states. This was done for the three most common products: FCR, aFRR, and mFRR. The existence of free bids in the aFRR and mFRR products has also been included. The results are shown in Table 4.4,

Table 4.5, and Table 4.6. Green cell colours indicate a more favourable evaluation of the product characteristic, an orange cell colour a less favourable evaluation. The main source for this information is the 2019 Ancillary Service Survey conducted by the European Network of Transmission System Operators for Electricity (ENTSO-E) in 2019 [7], complemented with own research of the national balancing frameworks of Member States and interviews with TSOs.

It becomes apparent that most countries already allow asymmetric provision in both the aFRR and mFRR product. This is an important enabler for renewables to participate. A large number of countries also has products that are contracted for less than 24 hours. Depending on the exact time resolution, this creates more or less opportunities for solar PV. There where contract periods are longer than 24 hours, but free bids exist, solar PV still has the opportunity to offer via the bidladder. Most problematic in most countries is the product lead time. In all countries, the capacity auction takes place at least a day in advance.

There where product characteristics are aligned for solar PV, the lack of a dedicated measurement and quantification method for solar is the last barrier that holds back participation in balancing. Several TSOs are actively working on solving this issue though:

- **Belgium**: *Company G (*Belgian grid operator), is conducting a study on its baseline methodologies for several balancing products, in which the authors were involved. They are also looking at baselines for solar PV as part of that effort. The results of this study have not yet been published.
- **Germany**: SERENDI-PV project partner Next Kraftwerke has conducted tests in providing balancing with part of its German solar portfolio. A baseline methodology is tested out, using power production values of solar parks nearby the solar plant that is used for balancing. The results of this study have not yet been published.
- **Netherlands**: *Company F* (Dutch grid operator) has not yet a baseline methodology for solar PV but indicated in talks with the authors that they are open to receive proposals from market parties.
- **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. The learnings from the pilot would be integrated in the balancing market design by the end of 2021 [26].

We can conclude that participation of solar PV in European balancing is still in its infancy. Where several countries already integrate solar curtailment in their redispatch and congestion management actions, real-time balancing through FCR, aFRR, mFRR, or RR remains difficult. The historic origins of balancing product design still introduce hurdles for solar, such as the symmetry requirements, product duration, and auction lead times. A dedicated measurement and quantification method for solar PV usually forms an additional hurdle. Several European TSOs are addressing these issues in pilot projects and consultations. It can therefore be expected that the regulatory landscape for solar PV participation in balancing will change significantly in the next years.

It should be noted that some of the hurdles presented above can be mitigated by the balancing service provider by building a solar portfolio with a larger geographical spread. The range of sun hours in a day can be increased and the impact of local weather events on forecasting reliability can be decreased. Combining solar PV with other variable or non-variable renewable technologies can also help creating a more easily controllable power output for balancing purposes.

Table 4.4: Overview of FCR product characteristics in selected Member States (source: own analysis)

Country	Providers	Product asymmetry	Contract period	Lead time
AT	Generators only	Symmetric	<24h	>24h
BE	Generators + Load + Pump Storage + Batteries	Symmetric	<24h	>24h
DE	Yes Generators + Load + Pump Storage + Batteries	Symmetric	<24h	>24h
DK	All but batteries	Asymmetric	<24h	>24h
ES	*Obligatory 24/7 service for generators and pumped storage*			
FI	Generators + Load + Batteries	Symmetric	<24h	>24h
FR	Generators + Pump storage	Symmetric	<24h	>24h
GR	Generators only	Asymmetric	<24h	>24h
HU	Generators + Batteries	Symmetric	<24h	>24h
NL	Generators only	Symmetric	<24h	>24h
PT	Generators only	Symmetric	<24h	>24h
RO	Generators only	Symmetric	<24h	>24h
SE	Generators only	Symmetric	>=24h	>24h
SI	*Obligatory 24/7 service for generators*			

Table 4.5: Overview of aFRR product characteristics in selected Member States (source: own analysis)

Country	Providers	Product asymmetry	Contract period	Lead time	Free bids
AT	All but batteries	Asymmetric	<24h	>24h	no
BE	Yes Generators + Load + Pump Storage + Batteries	Asymmetric	<24h	>24h	yes
DE	Generators + Load + Pump Storage + Batteries	Asymmetric	<24h	>24h	yes
DK	All but batteries	Asymmetric	>=24h	>24h	yes
ES	Generators only	Asymmetric	<24h	>24h	no
FI	Generators only	Asymmetric	<24h	>24h	no
FR	Generators + Pump storage	Asymmetric	<24h	>24h	Yes
GR	Generators only	Asymmetric	<24h	>24h	No
HU	Generators + load	Asymmetric	<24h	>24h	No
NL	Generators only	Asymmetric	<24h	>24h	Yes
PT	Generators + pump storage	Asymmetric	<24h	>24h	No
RO	Generators only	Symmetric	<24h	>24h	No
SE	Generators only	Asymmetric	<24h	>24h	No
SI	Generators + pump storage	Symmetric	Year(s)	Year(s)	No

Table 4.6: Overview of mFRR product characteristics in selected Member States (source: own analysis)

Country	Providers	Product asymmetry	Contract period	Lead time	Free bids
AT	All but batteries	Asymmetric	<24h	>24h	no
BE	Generators + Load + Pump Storage + Batteries	Asymmetric	<24h	>24h	yes
DE	Generators + Load + Pump Storage + Batteries	Asymmetric	<24h	>24h	yes
DK	All except batteries	Asymmetric	>=24h	>24h	yes
ES	Generators only	Asymmetric	<24h	>24h	yes
FI	All but batteries	Asymmetric	>=24h	Week(s)	yes
FR	All except batteries	Asymmetric	>=24h	Year(s)	Yes
GR	Generators only	Asymmetric	<24h	N/A	Yes
HU	Generators + load	Asymmetric	<24h	>24h	No
NL	All	Asymmetric	>=24h	>24h	Yes
PT	All but batteries	Asymmetric	<24h	N/A	No
RO	Generators only	Asymmetric	<24h	>24h	No
SE	Generators + load	Asymmetric	>=24h	Month(s)	Yes
SI	Generators + load	Asymmetric	Year(s)	Year(s)	No

4.5.4 European Harmonisation of balancing power

To ensure a more efficient procurement of balancing power and to create a level-playing field, the European Commission adopted the Electricity Balancing Guideline (EB GL)(Commission Regulation 2017/2195) to harmonize the European balancing markets [21]. The ENTSO-E is tasked to oversee its implementation, and has launched a number of initiatives to harmonize the existing balancing products in Europe:

- The FCR cooperation: harmonizing the FCR product [27]
- PICASSO: The Platform for the International Coordination of Automated Frequency Restoration and Stable System Operation (PICASSO) is the implementation project for the establishment of the European aFRR-Platform [28]
- Nordic aFRR: The Nordic TSOs will establish a regional balancing capacity market for aFRR balancing capacity [29]
- MARI: The Manually Activated Reserves Initiative (MARI) is the implementation project for the establishment of the European mFRR-Platform [30]
- TERRE: The Trans-European Replacement Reserves Exchange (TERRE) is the implementation project for the establishment of the European RR-Platform [31]
- Imbalance Netting: The International Grid Control Cooperation (IGCC) is the implementation project for the establishment of the European imbalance netting platform [32]

These projects are in different stages of development. For example, the imbalance netting is fully implemented between the participating TSOs. The FCR cooperation is up and running, with eleven TSOs now procuring FCR via a common auction platform. PICASSO is scheduled to be implemented by the end of 2021, while MARI should be implemented in the course of 2022. Implementation of TERRE is ongoing.

4.6 The need for new ancillary services

Regulation on grid integration and operations will never be finished. It will need to be updated continuously to adapt to the changes at both the demand and the supply side of the electricity market.

How old regulation can backfire and even lead to dangerous situation, can be illustrated by a German example. In 2008, Germany updated its grid compliance requirements for PV invertors [33]. Seeing the rise in distributed energy generation, system planners deemed it necessary to have solar installations disconnect when the mains frequency would reach 50.2 Hz – indicating a large oversupply in the grid.

Five years later, it had become apparent that such single threshold intervention posed a threat to system stability instead of helping it. By that time, solar systems had seen a massive growth in Germany. The rule would lead GWs of solar assets to disconnect from the grid at exactly the same time, potentially destabilizing the entire EU grid. In 2011, the 50.2 rule was therefore replaced with a droop control requirement for new PV invertors [34], which also applied to existing solar plants after a 2012 extension of the requirements.

Whereas old regulation on ancillary services can form a threat, failing to introduce new regulation can be equally problematic. In Section 4.2, we listed a number of potential grid services that solar PV could deliver. One of them is not procured in European member states: ramp rate control. This might have to change in a future with a high penetration of solar PV. During mornings and evenings, when the power output of solar increases and decreases rapidly, the net load to be covered by synchronous generators changes very fast. Such rapid fluctuations require more frequency support in the form of FCR and aFRR. The ramp rates will also challenge the technical capabilities of conventional power plants.

The result is, paradoxically, that higher solar penetrations, require more synchronous generators to be running to compensate the ramps and provide balancing [35]. The excess of power leads to negative prices, higher CO_2 emissions, and the need for more curtailment. This is also shown in the illustration below, where a scenario with so-called dispatchable solar (i.e. solar output can be controlled) and without are compared.

The provision of ramp rate control services by converter-interfaced solar PV could solve this problem. It already exists in for example Puerto Rico [36], and in Europe the Irish TSO EirGrid [37] has implemented measures for smoothening power output or variable renewables. Other Member States should consider investigating the creation of this new ancillary service too. Since it impacts the power that can be sold in the power exchanges, a regulated or market-based remuneration would be appropriate.

Other ancillary services like voltage support are currently part of the grid requirements, as discussed in Section 4.4. They are usually not remunerated, even though they represent an (opportunity) cost for solar PV project owners. Regulators should consider a regulatory framework in which these services are procured in a market, like most balancing products, or at least receive a regulated compensation.

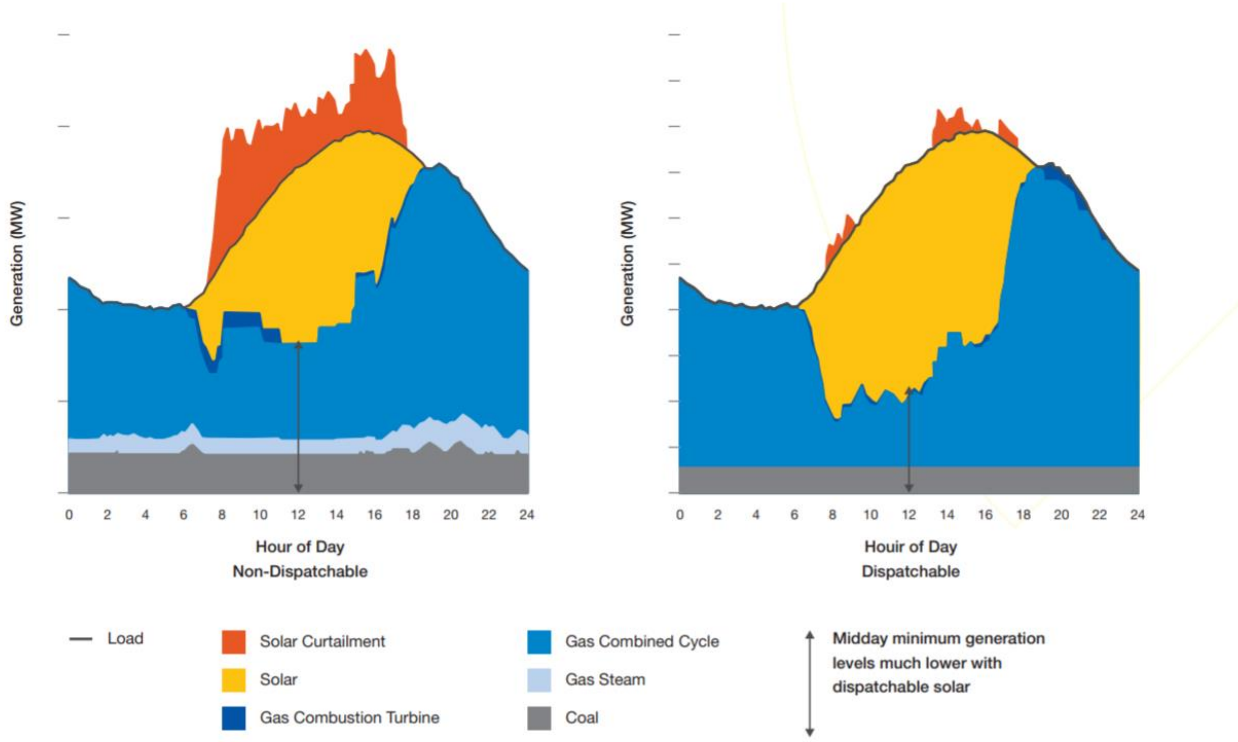

Figure 4.6 : Comparison of the need for spinning thermal power plants to provide balancing and ramping at high levels of solar penetration, in a case where solar output can and cannot be controlled (dispatchable versus non-dispatchable) (source: [35])

4.7 Conclusion

In this subtask, the regulatory framework for the connection of solar PV assets to the grid and their participation in ancillary services has been assessed. From a technical point of view, convertor-interfaced solar PV assets can provide several grid-supporting services, either based on the system state or an external trigger.

In Europe, a set of ancillary services such as behaviour in cases of large frequency and voltage deviations, voltage support, and curtailment for congestion management, are prescribed in the grid connection requirements. These have been harmonized on the European level through the NC RfG. Still, one observes considerable difference in categorization of assets depending on their size. National regulators still have a lot of leeway to define the specific technical characteristics of each requirement. Generally speaking, the grid connection requirements increase the ‘grid friendliness’ of solar PV in Europe.

The important subset of services called balancing power, is contracted by TSOs to support frequency control. These balancing power products vary widely between Member States, but also here, European harmonization is on its way thanks to the EB GL. In practice, solar PV does not yet actively participate in balancing products like FCR , aFRR, and mFRR, due to a number of barriers in the design of balancing products. These need to be addressed by regulators. The most important barriers are the lack of appropriate measurement and quantification methods for the delivered balancing power by solar PV, and longer contract periods and/or lead times. Further work is needed by regulators to open balancing products to solar plants. A number of pilot projects and studies are currently being conducted by European grid operators to address several of the aforementioned issues.

Besides the improvements needed in the grid connection requirements and the balancing product designs, European regulators should consider introducing a ramp rate control product. At higher levels of solar PV penetration, the ramp rates in the net demand that need to be covered by synchronous generators will demand large-scale curtailment and running peaker plants. Convertor-interfaced solar can provide ramp rate control, so this functionality should be used. Regulators also need to address renewable support schemes that disincentivize solar PV from participating in grid support services, and the need for more coordination between DSOs and TSOs.

5 References

[1] Eurostat, "Home - Eurostat." https://ec.europa.eu/eurostat (accessed May 03, 2021).

[2] RES LEGAL Europe, "LEGAL SOURCES ON RENEWABLE ENERGY," Feb. 15, 2021. http://www.res-legal.eu/home/ (accessed May 03, 2021).

[3] IEA PVPS Task 14, "Data Model for PV Systems," p. 52, 2020.

[4] *Network code on requirements for grid connection of generators*. 2016. [Online]. Available: https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=OJ%3AJOL_2016_112_R_0001

[5] ENTSO-E, "ENTSO-E Implementation Monitoring Active Library," *ENTSO-E*, May 03, 2021. https://www.entsoe.eu/active-library/codes/cnc/ (accessed May 03, 2021).

[6] ENTSO-E, "Electricity Balancing in Europe: An overview of the European Balancing makret and Electricity Balancing Guideline," Jan. 2018.

[7] ENTSO-E, "Survey on Ancillary Services Procurement, Balancing Market Design 2019," May 2020. Accessed: May 03, 2021. [Online]. Available: https://eepublicdownloads.entsoe.eu/clean-documents/mc-documents/200505_WG_AS_survey_ancillary_services_2019.pdf

[8] European Commission, "2030 climate & energy framework," *Climate Action - European Commission*, Nov. 23, 2016. https://ec.europa.eu/clima/policies/strategies/2030_en (accessed May 03, 2021).

[9] J. Christiansen, "SolarPower Europe EU Market Outlook," p. 60, 2019.

[10] R. Lacal Arantegui and A. Jäger-Waldau, "Photovoltaics and wind status in the European Union after the Paris Agreement," *Renewable and Sustainable Energy Reviews*, vol. 81, pp. 2460–2471, Jan. 2018, doi: 10.1016/j.rser.2017.06.052.

[11] SolarPower Europe, ETIP PV, "Solar Skins: An opportunity for greener cities." Jun. 19, 2019.

[12] L. Kitzing, C. Mitchell, and P. E. Morthorst, "Renewable energy policies in Europe: Converging or diverging?," *Energy Policy*, vol. 51, pp. 192–201, Dec. 2012, doi: 10.1016/j.enpol.2012.08.064.

[13] G. Masson and J. I. Briano, "REVIEW AND ANALYSIS OF PV SELF-CONSUMPTION POLICIES," p. 82, 2016.

[14] M. Alolo, A. Azevedo, and I. El Kalak, "The effect of the feed-in-system policy on renewable energy investments: Evidence from the EU countries," *Energy Economics*, vol. 92, p. 104998, Oct. 2020, doi: 10.1016/j.eneco.2020.104998.

[15] POLIMP, "Renewable Energy Support Policies in Europe | Climate Policy Info Hub." https://climatepolicyinfohub.eu/renewable-energy-support-policies-europe (accessed May 03, 2021).

[16] Department of the Environment, Climate and Communications, "Renewable Electricity Support Scheme (RESS)." https://www.gov.ie/en/publication/36d8d2-renewable-electricity-support-scheme/ (accessed May 03, 2021).

[17] Emilliano Bellini, "Lithuania announces first renewables auction and €4.5 million in solar rebates this year," *pv magazine International*. https://www.pv-magazine.com/2019/04/29/lithuania-announces-first-renewables-auction-and-e4-5-million-in-solar-rebates-this-year/ (accessed May 03, 2021).

[18] SolarPower Europe, ETIP PV, "Photovoltaic power plants in Slovenia," *Balkan Green Energy News*, May 27, 2019. https://balkangreenenergynews.com/photovoltaic-power-plants-in-slovenia/ (accessed May 03, 2021).

[19] E. Lambert *et al.*, "Practices and Architectures for TSO-DSO Data Exchange: European Landscape," in *2018 IEEE PES Innovative Smart Grid Technologies Conference Europe (ISGT-Europe)*, Sarajevo, Bosnia and Herzegovina, Oct. 2018, pp. 1–6. doi: 10.1109/ISGTEurope.2018.8571547.

[20] C. S. Demoulias *et al.*, “Ancillary Services Offered by Distributed Renewable Energy Sources at the Distribution Grid Level: An Attempt at Proper Definition and Quantification,” *Applied Sciences*, vol. 10, no. 20, p. 7106, Oct. 2020, doi: 10.3390/app10207106.

[21] *Guideline on Electricity Balancing*. 2017. [Online]. Available: https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=CELEX%3A32017R2195

[22] “Regelenergie & Regelleistung - was ist das?,” Nov. 04, 2010. https://www.next-kraftwerke.de/wissen/regelenergie (accessed May 03, 2021).

[23] Elia System Operator, “Study Report: Delivery of downward aFRR by wind farms,” Oct. 2015.

[24] “Renewable energy control center | Red Eléctrica de España.” https://www.ree.es/es/actividades/operacion-del-sistema-electrico/centro-de-control-de-energias-renovables (accessed May 05, 2021).

[25] IPTO, *Terms and Conditions for Balancing Service Providers*. 2020.

[26] EnergiNet, “Milestone: Wind turbines can balance the electricity grid.” https://en.energinet.dk:443/About-our-news/News/2020/12/16/Milestone-Wind-turbines-can-balance-the-electricity-grid (accessed May 05, 2021).

[27] ENTSO-E, “European Harmonisation of Frequency Containment Reserves (FCR),” *entsoe.eu*. https://www.entsoe.eu/network_codes/eb/fcr/ (accessed May 03, 2021).

[28] ENTSO-E, “European Harmonisation of aFRR: PICASSO,” *entsoe.eu*. https://www.entsoe.eu/network_codes/eb/picasso/ (accessed May 03, 2021).

[29] ENTSO-E, “European Harmonisation of the Nordic aFRR capacity markets,” *entsoe.eu*. https://www.entsoe.eu/network_codes/eb/nordic-afrr-capacity-markets/ (accessed May 03, 2021).

[30] ENTSO-E, “European Harmonisation of Manually Activated Reserves Initiative,” *entsoe.eu*. https://www.entsoe.eu/network_codes/eb/mari/ (accessed May 03, 2021).

[31] ENTSO-E, “European Harmonisation of Replacement Reserves: TERRE,” *entsoe.eu*. https://www.entsoe.eu/network_codes/eb/terre/ (accessed May 03, 2021).

[32] ENTSO-E, “European Harmonisation on Imbalance Netting: IGCC Merger,” *entsoe.eu*. https://www.entsoe.eu/network_codes/eb/imbalance-netting/ (accessed May 03, 2021).

[33] *Technical Guideline: Generating Plants Connected to the Medium-Voltage Network*. 2008. [Online]. Available: https://erranet.org/download/generating-plants-connected-to-medium-voltage-network/

[34] DNV, “The German 50.2 Hz problem,” *DNV*. https://www.dnv.com/cases/the-german-50-2-hz-problem-80862 (accessed May 03, 2021).

[35] SolarPower Europe, “Grid Intelligent Solar, Unleashing the Full Potential of Utility-Scale Solar Generation in Europe,” Dec. 2018. [Online]. Available: https://www.solarpowereurope.org/grid-intelligent-solar-how-solar-helps-stabilise-electric-grids/

[36] V. Gevorgian and S. Booth, “Review of PREPA Technical Requirements for Interconnecting Wind and Solar Generation,” National Renewable Energy Laboratory. [Online]. Available: https://www.nrel.gov/docs/fy14osti/57089.pdf

[37] EirGrid and Soni, “System Services Consultation – New Products and Contractual Arrangements,” Jun. 2012. [Online]. Available: http://www.eirgridgroup.com/site-files/library/EirGrid/System-Services-Consultation-New-Products-and-Contractual-Arrangements-June_2012.pdf

[38] IRENA, “Data & Statistics,” */Statistics*. /Statistics (accessed May 27, 2021).

Annex A: Interview grid operators about grid integration of Solar PV in European Grids

Part 1: Knowledge on solar PV installations and collaboration between TSO & DSO

We would like to know if you have sufficient information on the solar assets, how you gather data on them, and how you work together with other grid operators in this respect.

Q: Do you gather detailed information about solar assets in your grid? From which size onwards and on which voltage levels? What are the main properties you collect?

Q: How is this information being gathered? Part of grid connection request? Linked to subsidy request?

Q: Is this information shared with other actors (grid operators, regulator, government agencies, market parties)? Does this happen through shared databases, common portal,…?

Part 2: Impact of PV today

We would like to get an idea of the impact solar PV has in your grid today.

Q: Do you actively monitor the impact of solar PV in your grid? What are the general observations? If not, what is your general feeling about the impact?

Q: Do you face power quality issue due to solar PV?

Q: Do you face congestion issues due to solar PV?

Q: Did you have to do grid reinforcements due to solar PV in the past or do you think this will be needed in the future?

Q: Does the integration of solar PV into the grid has an impact on grid tariffs or do you take solar PV injection into account (directly or indirectly) when calculating grid tariffs (time dependent, total local peak power,…)?

Q: Do you need to activate more balancing reserves or redispatch due to solar PV? (if you have this means)

Q: Does solar PV have an impact on generation adequacy today and in the next 5 years?

Part 3: Obligatory connection requirements to help integrate solar PV

We would like to investigate whether connection requirements are in place to limit the (negative) impacts of rising solar PV capacity in your grid.

Q: Do you apply grid connection requirements to solar PV installations specifically designed to limit their impact on the grid? Examples are 50.2 disconnection rules, connection capacity caps, reactive power obligations, remote controllability for redispatch…

Q: Do you believe the current grid connection requirements are sufficient to deal with rising solar PV capacity?

Part 4: Ancillary services

We would like to know if solar PV can or must offer ancillary services, which helps their integration into the grid.

Q: Do you procure ancillary services? If so, can or must solar PV installations participate in some or all of them? List the ones that are applicable: FCR, aFRR, mFRR, black start, congestion management, voltage control,…

Q: Are the technical requirements for these services technology neutral? If not, what are the specific rules for solar PV?

Q: How is the baseline calculated to determine if the service is delivered correctly?

Annex B: Survey

Questionnaire: Databases and Registration of PV

Thank you for participating in this survey in the context of the European research project SERENDI-PV. In this questionnaire, we will study if and how Solar PV systems in your grid area are being registered in one or more 'databases'. This way, we will be able to evaluate the landscape of approaches in Europe in keeping track of the growth of decentralised renewable energy production installations.

After filling out some general information about the database you work with in your grid area, you are asked to indicate whether the listed parameters are included in your database and whether the presented statements are valid. This is done by checking the appropriate boxes. If the question cannot simply be answered by "True" or "False", you can tick the third option "Extra notes given below" and elaborate further in the "Notes"-section below every section.

If you have questions about this questionnaire or want to provide more in-depth feedback, please contact the researchers responsible for this survey: Nadia Wiesé (wiese@next-kraftwerke.be) and Elias De Keyser (dekeyser@next-kraftwerke.be)

*Required

General Information

1. Name of your organisation *

If you prefer not to disclose your organization's name, please indicate the country you are active in.

____

2. What role does your organisation play in the electricity system? *

Mark only one oval.

- ⬭ DSO
- ⬭ TSO
- ⬭ Regulator
- ⬭ Government Instance
- ⬭ Other: ________________________________

3. Do you make use of a central register or database to keep track of the solar PV assets in your grid area? *

   Mark only one oval.

   - Yes
   - No *Skip to section 4 (Thank you)*

4. Who hosts & maintains the database? *

   Mark only one oval.

   - our organization hosts, maintains and uses the database alone
   - our organization hosts and maintains the database alone, but others can consult it
   - we host, maintain, and use the database together with others
   - the database is hosted and maintained by another organisation, but we can consult it
   - Other: ______________________

5. What is the common name used to refer to this database (if any)?

   ____

6. What is the geographic scope of the database? *

   For example: country, region, LFC block, DSO area,...

   ____

7. Are plant owners obliged to register their solar plant? *

Tick all that apply.

- [ ] Yes, always
- [ ] When they are larger than a certain size
- [ ] When they want to receive government support or certificates of origin
- [ ] It is purely voluntary

Other: [ ] ______________________

8. Is the database mostly available for third parties (e. g. public)?

Mark only one oval.

- ( ) No, it is strict confidential.
- ( ) Yes, it is mostly public available.
- ( ) No, it is only shared with certain third parties.
- ( ) Other: ______________________

9. Do you find shared databases on solar PV with other organisations in the electricity sector useful? *

Mark only one oval.

- ( ) We don't have a shared database, and we don't think it would be useful.
- ( ) We don't have a shared database, but we think it would be useful.
- ( ) We do have a shared database, and we like it this way.
- ( ) We do have a shared database, but we would prefer to use our own database which is not shared.
- ( ) Other: ______________________

10. Do you have additional information about the setup of the database and the obligation of solar plant owners to register their asset?

Parameters collected in the database

11. Which properties of the solar plant are being registered in the database? *

Tick all that apply.

	Included	Not included	Extra notes given below
Project name e.g. (name new installation)	☐	☐	☐
Identification number	☐	☐	☐
County	☐	☐	☐
City	☐	☐	☐
Address	☐	☐	☐
Coordinates: Longitude	☐	☐	☐
Coordinates: Latitude	☐	☐	☐
Type of Feed-in Tariff (FIT)	☐	☐	☐
Operational metering data with monthly (or yearly) resolution	☐	☐	☐
Operational metering data with daily (or smaller) resolution	☐	☐	☐

12. General data: additional notes

13. What site configuration data is registered in the database? *

Tick all that apply.

	Included	Not included	Extra notes given below
Type of consumer (household, industry, ...)	☐	☐	☐
Type of system (rooftop, ground mounted, ...)	☐	☐	☐

14. Site data: additional notes

15. Which detailed technical data is collected in the database? *

Tick all that apply.

	Included	Not included	Extra notes given below
Type of module	☐	☐	☐
DC-power	☐	☐	☐
AC-power	☐	☐	☐
Inverter power	☐	☐	☐
Inverter manufacturer	☐	☐	☐
All modules have the same orientation (yes/no)	☐	☐	☐
Main orientation	☐	☐	☐
Second orientation	☐	☐	☐
Main tilt angle	☐	☐	☐
Second 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 that can be fed into the grid	☐	☐	☐

Energy capacity storage if present (e.g. battery)	☐	☐	☐
Inverter power (battery inverter)	☐	☐	☐

16. Technical data: additional notes

Thank you

Thank you for participating in this questionnaire! If you have questions or you want to provide more additional information, you can send an email to: wiese@next-kraftwerke.be and dekeyser@next-kraftwerke.be.

Annex C: Installed PV capacity 2020

Table 5.1: Overview of the installed PV capacity at the end of 2020 (data source: [38])

Installed PV capacity 2020 [MW]	
Ranked by capacity	
Germany	53,781
Italy	21,594
Spain	11,785
France	11,724
Netherlands	10,213
Belgium	5,646
Poland	3,936
Greece	3,247
Austria	2,220
Czechia	2,073
Hungary	1,953
Sweden	1,417
Romania	1,387
Denmark	1,300
Bulgaria	1,073
Portugal	1,025
Slovakia	593
Finland	391
Slovenia	267
Cyprus	200
Luxembourg	195
Malta	184
Lithuania	148
Estonia	130
Croatia	85
Ireland	40
Latvia	7