IEA INTERNATIONAL ENERGY AGENCY

Flexible resources for flexible transmission system operation

IEA-PVPS Task 14: “High Penetration of PV Systems in Electricity Grids” Subtask 3: High penetration solutions for central PV generation scenarios

PHOTOVOLTAIC
POWER SYSTEMS
PROGRAMME

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List of acronyms

CCGT	Combined Cycle Gas Turbine
CE	Continental Europe
CHP	Combined Heat and Power
CM	Congestion Management
DG	Distributed Generation
DR	Demand response
DSO	Distribution System Operator
EHV	Extra High Voltage
FACTS	Flexible Alternating Current Transmission System device
FCR	Frequency Containment Reserve
FFR	Fast Frequency Response
FRRa	Automatic Frequency Restoration Reserve
FRRm	Manual Frequency Restoration Reserve
GPRS	General Packet Radio Service
GPS	Global Positioning System
GSM	Global System for Mobile communications
HV	High Voltage
HVDC	High Voltage Direct Current link
ICT	Information and Communications Technology
LCC HVDC	Line Commutated Converter HVDC
LDC	Local Distribution Company
LoRa	Long Range standard
LPWAN	Low-Power Wide-Area Network
LVRT	Low Voltage Ride Through
OCGT	Open Cycle Gas Turbine
PHS	Pumped Hydroelectric Storage
PV	Photovoltaic
RES	Renewable energy sources
RMR	Reserve Margin Restoration
ROCOF	Rate Of Change Of Frequency
RR	Replacement Reserve
TSA	Transient Stability Analysis
TSO	Transmission System Operator
VC	Voltage Control
VIU	Vertical integrated utilities
VSC HVDC	Voltage Source Converter HVDC

Executive Summary

The dramatic increase of PV generation implies several challenges in transmission and distribution system operation. As for transmission, major issues relate to the variability, uncertainty, reduction of inertia and regulation capabilities, with consequent higher needs in flexibility resources requirements. Flexibility is considered as the ability of the power system to deploy its resources with the aim to match with changes in “net load” (e.g. load minus DG output including variable generation) ensuring a stable and a secure operation. In particular, high PV penetration significantly affects the daily profile of “net load”: lower net load in central daylight hours involves the risk of over-generation since a minimum amount of traditional generation is required for operational security (e.g. balancing reserve); in the evening, the decreasing PV output, which occurs together with the evening load demand ramp, exacerbates the upward ramps of net load with consequent risk of inadequate system response. The above concerns are further increased by the progressive decommissioning, due to loss of market competitiveness, of thermal power plants i.e. the main traditional resources of flexibility. New, highly performing flexibility resources are therefore gaining more and more importance.

This report provides a review of present and expected scenarios about flexibility in system operation. It summarizes and integrates results of a survey involving national experts in six countries, namely Belgium, Germany, Greece, Italy, Japan, and Switzerland. Information is provided about: i) power systems and markets with presence of PV; ii) existing flexibility resources; iii) innovative flexibility resources, including demand response and PV output management for system operation. Contents are structured in order to support scenario development in future PV integration studies.

The main conclusions of the report are the following:

- High reliability in PV forecast can be achieved in the short-term (e.g. 1 hour or less). However, not all the flexibility resources can be activated compatibly with this time frame. Consequently more and faster flexibility resources are needed (e.g. improving the thermal power performances of installing battery energy storage systems).

- A large amount of renewable energy sources (RES) requires probabilistic approaches for the assessment of balancing reserve requirements aimed to compensate RES forecast uncertainty, accepting a certain risk in order to limit expensive over-estimations.

- In order to face the changes in net load daily profile, new highly performant flexibility resources are needed, such as: i) thermal power plants allowing shorter starting time, lower number of hours of continuous operation, smaller minimum “off” time, faster ramping capability; ii) distributed generation (DG) output modification; iii) demand response (DR); iv) battery storage.

- DR is endorsed in order to be exploited for peak shaving, power balancing and congestion management. Participation of electric vehicles in DR is considered a reasonable opportunity.

- PV output curtailment/modification can be seen as a sort of ancillary service due mainly to grid congestions and system balance but also for voltage deviations and for system voltage-related stability.

- Provision of flexibility necessarily means a reduction of energy production of RES (e.g. for upward power reserve provision), unless storage units are installed. Accordingly, in order to realize the utilization of flexibility of RES, it is inevitable to establish a regulatory framework and market mechanism.

- DR and DG output modification involve the need of smart grids based on ICT infrastructures allowing observability and controllability of the grid, also at distribution level. Many ICT solutions are or will be available in the next future (wireless communication internet; Low-Power Wide-Area Networks; etc.). Accurate studies need to be performed in order to highlight the advantages and the drawbacks of each option.

- Despite the present high costs, battery energy storage BES can be one of the most promising kinds of flexible resources with high performances in terms of response speed to power unbalances due to PV variability and uncertainty following fast meteorological changes. BES represents, also associated with variable renewables, a promising solution for synthetic inertia and fast frequency control provision.

- PV may be associated to storage and possibly be kept in de-loaded operation in order to supply a fast frequency response.

1 Introduction

High penetration of PV generation is expected to create specific challenges in terms of transmission system operation, introducing variability, uncertainty, null inertia with consequent higher complexity in flexibility resources provision. Moreover many thermal power plants, which are one of the main resources of flexibility, e.g. in terms of active power regulation and system inertia, are facing a progressive decommissioning since they are less competitive than renewable resources. Flexibility is considered as the ability of the power system to deploy its resources with the aim to match with changes in "net load" ensuring a stable and a secure operation. The definition and comprehensive description can be found in many publications including "The Power of Transformation"[1].

The present IEA Task 14 Subtask 3 Activity 4 report is aimed to collect structured information on present and expected scenarios about flexibility in system operation. It summarizes and integrates results of a survey involving national experts from industries and research in 6 countries, namely Belgium, Germany, Greece, Italy, Japan and Switzerland.

The results of this report will be followed and used in the subsequently planned report of Subtask 3 Activity 5 "Survey and case study of innovative transmission system operation of transmission level with generation forecast and innovative flexibility resources".

1.1 Motivation

PV generation is characterized by variability, since its availability follows daily and annual patterns, and by uncertainty, depending on weather conditions. Variability involves the more and more challenging need of proper conventional generation capacity and storage. Uncertainty involves the a-head allocation of reserve and the real time balancing. Another challenge to deal with is the lack of system inertia related to PV penetration and the related displacement of conventional generation.

Like other RES, PV must be exploited when the primary source (solar irradiation in this case) is available, otherwise it is lost. Moreover, PV systems are often of small size and connected to the distribution system. Connection is realized via power electronic converters. These basic recalls motivate the need for actions aimed to boost PV integration in the power systems and electricity markets, among which are: I) improvement of ramp rate, reduction of minimum operation and start-up time reduction of existing and new thermal and hydro generators; II) improvement of PV generation forecast; III) demand activation; IV) exploitation of energy storage by means of pumped storage power plants and/or batteries, V) PV output modification, VI) interconnections exploitation for reserve capacity sharing among control areas and for electricity markets integration.

1.2 Goal of the activity

Structured information about flexible resources for power system operation is retrieved in order to support scenarios development in future PV integration studies. The aim is to

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[1] International Energy Agency (IEA): "The Power of Transformation -Wind, Sun and the Economics of Flexible Power Systems- (2014)
https://www.iea.org/publications/freepublications/publication/the-power-of-transformation---wind-sun-and-the-economics-of-flexible-power-systems.html

support, in first instance, experts from research centres but also utilities and industry and regulatory authorities involved in definition of perspective scenarios concerning the power system operation.

1.3 Report structure

Keeping in mind the aforementioned needs, the report is structured into the four following sections:

chapter no. 2 - power systems and markets with presence of PV;

chapter no. 3 - existing flexibility resources;

chapter no. 4 - innovative flexibility resources including demand-activation;

chapter no. 5 - PV output management for system operation;

Chapter 2 is aimed to compare different national situations.
Chapters 3 to 5 are meant to supply information for the analyses and simulations foreseen in Task 14 activities 3.6 and 3.7.

There is a substantial amount of existing studies(2,3,4,5,6,7) close to the scope of PVPS Task 14 Activity 3.4. However, the technological and regulatory situation of intermittent RE evolves rapidly. The present work has been prepared with the aim to provide up-to-date, synthetic information consistent with the needs of PVPS Task 14 Subtask 3.

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2 CIGRE Working Group C5.11: Market Design for Large Scale Integration of Intermittent Renewable Energy Sources (2013)

3 CIGRE WG C2-5_MARKET OPERATORS-Their Evolution, Current Organization and Future Structure, Brochure 626 (2015)

[4] International Energy Agency: “Empowering Variable Renewables, Options for Flexible Electricity Systems”. Grid Integration of Variable Renewables (GIVAR) programme - Phase I (2008).

[5] International Energy Agency: “Harnessing Variable Renewables: a Guide to the Balancing Challenge”. GIVAR programme - Phase II (2011).

6International Energy Agency: The Power of Transformation - Wind, Sun and the Economics of Flexible Power Systems (2014). GIVAR programme - Phase III (2014).

[7] The 21st Century Power Partnership: Flexibility in 21st Century Power Systems (2014)

2 Power systems and markets with presence of PV

This chapter collects the survey results about the present and expected situation of power systems and national practices about the electricity markets and PV integration. The aim is to provide proper information for scenario development to feed PV integration studies.

2.1 Present situation of power system

Many kinds of study can be carried out about the impact of high PV penetration on power system. Among these are:

- Load flow analysis - steady state assessment of power flows;
- Dynamic analysis - assessment of angle, voltage, frequency stability in case of large perturbations on power systems (under sound or degraded network conditions);
- Probabilistic/stochastic assessment of reserve requirements aimed to face RES variability and uncertainty.

This section provides general data useful for the above mentioned kinds of study.

2.1.1 Generation and Consumption

The Table 1 shows relevant statistics on PV generation and power consumption concerning the interviewed European countries.

Table 1: Statistics on power generation and consumption in the interviewed European countries

Generation and consumption	Belgium		Germany		Italy		Greece		Switzerland	
	Value	Year	Value	Year	Value	Year	Value	Year	Value	Year
Nominal frequency [Hz]	50		50	-	50		50		50	
Total net generation capacity [GW]	20.6	2015	189.4	2013	124.7	2013	17.35 (mainland)	ott-15	17.9	2014
PV capacity (nationwide) [GW]	**2.7**	**2015**	**37**	**08/2014**	**18.4**	**2013**	**2.6**	**ott-15**	**ca. 1.2**	**2015**
Hydroelectric generation capacity [GW]	0.1	2015	10.3	08/2014	14.5	2013	3.24	ott-15	12.97	2014
Hydroelectric pumped storage capacity [GW]	1.3	2015	6.5	2014	7.5	2013	0.7	ott-15	3.717	2014
Thermal generation capacity [GW] (including geothermal and biomass)	8	2015	88.5	2013	75.8 all 3 OCGT 41.2 CCGT 31.6 Convent.	2013	10.22	ott-15	1.021	2014
Thermonuclear generation capacity [GW]	5.9	2015	12.1	2013	0	2015	0	ott-15	3.485	2015
Wind generation capacity [GW]	1.7	2015	38	08/2014	8.5	2013	1.457	ott-15	0.06	2014
Peak/Off peak load (nationwide) [GW]	13.5/5.7	2015	86.9	2011	51.6/18.7	2014	9.161/3.3	2013	9.662	2015
Total energy consumption [GWh] (no storage)	81315	2012	518000	2014	330043	2013	50742 (mainland)	2014	57500	2014
Share of PV on total elect. consumption [%]	**2.9**	**2012**	**6**	**2014**	**6.5**	**2013**	**7 (mainland)**	**2014**	**1.5**	**2014**
Total energy cross-border exchange [GWh]	23760	2012	-35700	2014	42138 (imp)	2013	8588.9	2014	42900 export 37400 import	2014
Electricity consumption by storage [%] (Hydro Pumped Plants and others)	2.5	2014			0.9	2013	0.34	2014	2.35	2014
Total net energy generated by national generators [GWh]	83071	2012	562000	2014	289803	2013	41258.6	2014	69633	2014
Share of energy generated by PV [GWh]	**2148**	**2012**	**34900**	**2014**	**21588**	**2013**	**3558**	**2014**	**Ca. 900**	**2014**
Share of energy gen. by hydroelectric [GWh]	1659	2012	24098	2014	54671	2013	3062	2014	39300	2014
Share of energy gen. by thermal [GWh]	31495	2012	317000 (fossil)	2014	198646	2013	30362	2014	3719	2014
Share of energy gen. by thermonuclear [GWh]	40295	2012	91800	2014	0	2013	0	2014	26370	2014
Share of energy gen. by wind [GWh]	2750	2012	55000	2014	14897	2013	3009	2014	108	2014
Share of installed PV capacity at HV level [%]	**/**	**/**	**6**	**08/2014**	**5.4**	**2013**	**2.2**	**2014**	**/**	**/**
Share of installed PV capacity at MV level [%]	**/**	**/**	**32**	**08/2014**	**61.4**	**2013**	**45.6**	**2014**	**/**	**/**
Share of installed PV capacity at LV level [%]	**/**	**/**	**61**	**08/2014**	**33.2**	**2013**	**52.2**	**2014**	**/**	**/**
Average size of PV systems [kW]	5	2015	17	2012	30.5	2013	46.36	2014	/	/

Further general data about Europe may be retrieved in "*Yearly Statistics & Adequacy Retrospect*" ([1]), published by ENTSO-E. For the sake of simplicity, Table 2 shows relevant statistics about the global ENTSO-E area (Continental Europe, Scandinavia, Isolated areas of Great Britain, Ireland, Iceland); data about each country are also included in [1].

Table 2: Statistics on power generation and consumption in ENTSO-E area; data provided by ENTSO-E

Generation and consumption	ENTSO-E area	
	Value	Year
Nominal frequency [Hz]	50	
Total net generation capacity [GW]	1015.1	2014 [1]
Solar capacity (nationwide) [GW]	**82.8**	2014 [1]
Hydroelectric generation capacity [GW]	202	2014 [1]
Hydroelectric pumped storage capacity [GW]	/	/
Thermal generation capacity [GW] (geothermal and biomass included)	452.5	2014 [1]
Thermonuclear generation capacity [GW]	126.5	2014 [1]
Wind generation capacity [GW]	122.8	2014 [1]
Peak/Off peak load (nationwide) [GW]	522/234	2014 [1]
Total energy consumption [GWh] (no storage)	3218390	2014 [1]
Share of solar on total elect. consumption [%]	**2.8**	2014
Total energy cross-border exchange [GWh]	445554 export 442620 import	2014 [1]
Electricity consumption by storage [%] (Hydro Pumped Plants and others)	47637	2014 [1]
Total net energy generated by all generators [GWh]	3268961	2014 [1]
Share of energy generated by solar [GWh]	**91727**	2014 [1]
Share of energy gen. by hydroelectric [GWh]	608392	2014 [1]
Share of energy gen. by thermal [GWh]	1333186	2014 [1]
Share of energy gen. by thermonuclear [GWh]	858890	2014 [1]
Share of energy gen. by wind [GWh]	249102	2014 [1]
Share of installed PV capacity at HV level [%]	n.a.	n.a.
Share of installed PV capacity at MV level [%]	n.a.	n.a.
Share of installed PV capacity at LV level [%]	n.a.	n.a.
Average size of PV systems [kW]	n.a.	n.a.

Table 3 shows relevant statistics about the Japanese power system. These data were retrieved from the Japanese Ministry of Economic, Trade, and Industry website ([2]), with the exception of the PV installed capacity [3].

Table 3: Statistics on power generation and consumption in Japan - [2]

Generation and consumption	**Value**	**Year**
Nominal frequency [Hz]	50/60	2014
Total net generation capacity [GW]	313.8	2014
PV capacity (nationwide) [GW]	**23.3**	**2014**
Hydroelectric generation capacity [GW]	22.6	2014
Hydroelectric pumped storage capacity [GW]	27	2014
Thermal generation capacity [GW] (geothermal and biomass included)	193.9	2014
Thermonuclear generation capacity [GW]	44.3	2014
Wind generation capacity [GW]	2.8	2014
Peak/Off peak load (nationwide) [GW]	(152/82)	2014
Total energy consumption [GWh] (no storage)	933000	2014
Share of PV on total elect. consumption [%]	**2.1**	**2014**
Total energy cross-border exchange [GWh]	0	2014
Electricity consumption by storage [%] (Hydro Pumped Plants and others)	0.6	2013
Total net energy generated by national generators [GWh]	936300	2014
Share of energy generated by PV [GWh]	**19400**	**2014**
Share of energy gen. by hydroelectric [GWh]	82300	2014
Share of energy gen. by thermal [GWh]	829600	2014
Share of energy gen. by thermonuclear [GWh]	0	2014
Share of energy gen. by wind [GWh]	5009	2014
Share of installed PV capacity at HV,MV level(≥50 kW) [%]	**69 (≥10 kW)**	**2015**
Share of installed PV capacity at LV level(< 50kW) [%]		
Share of installed PV capacity at LV level(< 10kW) [%]	**31 (< 10kW)**	**2015**
Average size[8] of PV systems [kW]	2400	2014

Concerning the United States, general information was achieved from the website of the U.S. Energy Information Administration "EIA" ([4]). The North American electrical power system (Quebec region included) is partitioned into four synchronous areas with nominal frequency of 60 Hz ([5]). Synchronous areas are connected via HVDC links and back-to-back substations (AC/DC/AC conversion). Asynchronous DC interconnections allow the coexistence of different adopted standards in the fourth synchronous areas operation.
The Table 4 summarizes general data of the North American system, on the basis of publicly available data ([4]-[6]).

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[8] Only PV systems that have more than 1,000 kW for the maximum output are included.

Table 4: Statistics on power generation and consumption in the United States of America ([4]-[6])

Generation and consumption	**Value**	**Year**
Nominal frequency [Hz]	60 [5]	
Total generation capacity [GW]	1172.6 [4]	2014
PV capacity (nationwide) [GW]	**18.3** [3]	2014
Hydroelectric generation capacity [GW]	78.8 [4]	2014
Hydroelectric pumped storage capacity [GW]	21.6 [4]	2014
Thermal generation capacity [GW] (geothermal and biomass included)	879.8 [4]	2014
Thermonuclear generation capacity [GW]	103.9 [4]	2014
Wind generation capacity [GW]	65.3 [4]	2014
Other generation[9] [GW]	3.3 [4]	2014
Peak load (nationwide) [GW]	767 [4]	2012
Total energy consumption [GWh] (no storage)	3863000 [6]	2014
Share of PV on total elect. consumption [%]	**0.6** ([4].[6])	**2014**
Total energy cross-border exchange [GWh]	/	/
Electricity consumption by Hydro Pumped Storage [%]	0.2 [4]	2014
Total net energy generated by national generators [GWh]	4103141 [4]	2014
Share of energy generated by PV [GWh] Share of energy generated by Solar PV	**24786** [4] 2439 [4]	2014
Share of energy gen. by hydroelectric conventional [GWh]	259366 [4]	2014
Share of energy gen. by thermal [GWh]	2750571 [4]	2014
Share of energy gen. by thermonuclear [GWh]	797167 [4]	2014
Share of energy gen. by other renewables Excluding Hydroelectric and Solar [GWh]	261523 [4]	2014
Share of installed PV capacity at HV level [%]	/	/
Share of installed PV capacity at MV level [%]	/	/
Share of installed PV capacity at LV level [%]	/	/
Average size of PV systems [kW]	/	/

2.1.2 Cross-border power balancing

In order to reduce the impact of the RES variations, it is effective to share power balancing capability across national borders. Nevertheless, power balancing sharing depends on the transmission capacity between areas and on the peculiarities of each national system. For instance, the Continental Europe (CE) grid is highly meshed in some areas and quite less in other ones. Low meshing implies reduced transmission capacity as in the case of the Italian grid, which is electrically long with some internal critical sections, highlighting six different market zones. Italy like other peripheral systems (e.g. Ireland) adopts the central dispatch practice involving dispatch instructions issued by the TSO to all parties; in CE, self-dispatch practice is adopted with single generators or portfolio of generators following an aggregated schedule of actions (start/stop/increase output/decrease). Different situations, within ENTSO-E borders, are summarized by a survey [7], periodically performed in order to have the snapshot of the current scenario.

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[9] Other energy sources including: batteries, hydrogen, purchased steam, sulfur, tire-derived fuels and other miscellaneous energy sources.

Cross-border power balancing is expected in Greece even if, in the near future, it is evaluated only with Italy. It is worth noting that the Italian and Greek systems are not only synchronously interconnected via the CE[10] and Balkans grids, but they are also interconnected by a 400 kV, 500 MW HVDC link.

The Italian transmission system operator TERNA is evaluating technical-economic feasibility of bilateral agreements for mechanisms for exchange of tertiary and secondary reserve.

Belgium buys operating reserve capacity abroad, e.g. Frequency Containment Reserve (FCR) (namely, primary frequency regulation reserves) in France & Frequency Restoration Reserve (FRR) (tertiary reserves) from other TSOs. The Belgian TSO Elia has participated in the International Grid Control Cooperation platform (IGCC[11]) since October 2012. The aim of IGCC is to optimise the balancing management of the system and the quality of electricity grid control. This coordination is intended to automatically compensate for any imbalances in opposite directions experienced by system operators avoiding activation of secondary reserves in opposite directions. Imbalance is shared between Austria, Germany, Belgium, the Netherlands, Denmark, Switzerland and the Czech Republic. Before reserve activation, imbalance volumes between regions are netted.

Table 5 summarizes the situations in the interviewed European countries.

Table 5: Cross-border power balancing in the interviewed European countries

	Cross-border power balancing
Belgium	Yes
Switzerland	Yes
Germany	Yes
Greece	Under Discussion
Italy	Under Discussion

No cross-border interconnections are present in Japan.

2.2 Present situation of markets

The Table 6 summarizes electricity market situation in the interviewed countries.

In Japan, retail power market was not fully deregulated until the year 2016, while there has been a voluntary nation-wide wholesale market operated by Japan Electricity Power Exchange (JEPX). The last part of the retail market, of residential sector, has been

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[10] Central Europe

[11] IGCC Participants: Amprion, 50Hertz, TransnetBW and TenneT DE (the four German transmission system operators), Energinet.dk (Denmark), CEPS (Czech Republic), Swissgrid (Switzerland), TenneT NL (The Netherlands), APG (Austria) and Elia (Belgium). See also http://www.elia.be/en/users-group/ad-hoc-taskforce-balancing/IGCC.

liberalized since 2016 April. The transmission/distribution sectors, which are currently within 10 vertically integrated power companies, are gradually being separated.

Unlike other countries, in the day-ahead market of Greece ([8]), uniform pricing still applies, reflecting the price of the most expensive offer to meet the predicted demand; zonal pricing has not been activated yet.

In Germany, it's certainly worth noting that no dispatching services are included in market structures.

Table 6: Present status of Market

	Belgium	**Greece**	**Germany**	**Italy**	**Switzerland**	**Japan**
Power system market regulated	Yes	yes	yes	yes	Yes	**No**
Market structure	Energy trading + dispatching	Energy trading + dispatching	Energy Trading	Energy trading + dispatching	Energy trading + dispatching	Only trading in private JPEX
Clearing price for electricity market	zonal m.p.[12]	pay as bid	zonal m.p.	zonal m.p.	Merit Order and one clearing price for the whole country	zonal m.p.
Electricity market time resolution	60 min (15min settlement)	60 min	15 min	60 min	15 min (but many energy products are traded on a 1h)	30min
Electricity market time horizon	intraday (5 min) and day ahead	from hours to day ahead	from hours (30 min) to day ahead	from hours to day ahead	Long term contracts, day ahead (spot market), intraday and after day	4 hours ahead & day ahead. 1 hour-ahead market will be established on April 2016
Remuneration scheme for ancillary services	pay as bid	pay as bid	pay as bid	pay as bid	pay as bid	/
Services included in the ancillary service market	FCR, FRRa, FRRm, Black Start, VC, CM	VC, FCR, FR, RMR	FCR, FRR, RMR	FRR, RMR, CM	FCR, FRR, RMR, VC, CM	/
Procurement scheme for not market regulated ancillary services	Bilateral Contracts Between TSO & producers. Market platform for free bids and activation	/	Bilateral contracts Between TSO/ISO & produces and consumers	bilateral contracts between TSO and producers	Bilateral Contract between TSO/ISO and producers, which in some cases are DSO	Supply and demand adjustment by vertically unified electric power company

PV generation is already integrated into electricity markets of Belgium, Germany, Italy, Switzerland (Table 7).

PV aggregation is used in Italy, Germany, and Switzerland.

In Switzerland, all PV power plants, which get FIT[13] from the Swiss national FIT program, are aggregated into one balancing group and put on the market. All other PV power plants are integrated into the balancing area of the DSO that performs its load forecast including these PV power plants.

In Italy, relevant PV power plants (with rated power higher than 10 MVA) can directly present energy bids in day-ahead electricity market; energy traders can perform bids

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[12] Marginal Price: in a given market zone, it is the offer/bid with the highest merit order that has been accepted.

[13] Feed-In Tariff: policy mechanism based on offering long-term contracts to renewable energy producers.

based on generation forecast of aggregated PVs. The publicly-owned company in charge of granting incentives for electricity generation from renewables[14] performs daily bidding activity in the day-ahead electricity market by means of aggregation of small PV systems ([9]).

Table 7: PV participation into electricity markets

	Belgium	Switzerland	Germany	Greece	Italy	Japan
PV generation integrated into energy market	Yes	Yes	Yes	No	Yes	no
Scheme of PV integration into market	Voluntary participation for size < 10kW Mandatory participation for size > 10kW: injection tariff. Under 10kW: net energy metering	All PV power plants which get FIT are aggregated into one balancing group.	Optional participation by means of aggregators for PV with appropriate meters	/	Direct participation for big PV plants. Optional participation by means of aggregators	/

2.3 Expected evolution of generation and demand

2.3.1 PV capacity

Looking at the expected evolution of PV capacity, shown in Table 8, it can be noted that PV is overall expected to grow significantly. The growth percentage, shown in the last column, is given by:

$$yearly\ percent\ growth\ rate = \left(\sqrt[no.years]{expected\ capacity/present\ capacity} - 1\right) \cdot 100$$

High percent increases are in general highlighted in those countries with low present capacity (Belgium, Greece, Switzerland).

Italy and Germany are the interviewed European countries with the highest PV present capacities. Despite the already large installed capacity amount, a significant growth, in GW, is further expected in the period 2013-2024.

A significant PV cumulative capacity is expected in Japan (64 GW by 2030 against 23.3 GW installed in 2014). That capacity is certainly a big challenge in an islanded grid like the Japanese one; it can be accommodated by displacing a large amount of conventional thermal and thermonuclear generation. The Japanese one is certainly an interesting national case about how to manage a very high PV penetration in terms of nation-wide balancing.

By 2021, on the basis of information available on the internet, expected cumulative PV installed capacity in U.S.A. is around 100 GW; the resulting annual percent increase is more than 27%.

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[14] GSE "Gestore dei Servizi Energetici", http://www.gse.it.

Table 8: expected evolution of PV installed capacity

	Expected cumulative amount [GW]	Voltage level	Horizon Year	Present cumulative amount	Reference Year	[%, yearly]
Belgium	4.7 (moderate)	MV. LV	2020	2.7	2015	11.7
	6.5 (high)	MV. LV	2020			19.2
Germany	39	MV. LV	2015	37	08/2014	4
	41.5	MV. LV	2016			5
	58[15]	/	2024			4.1
Italy	23.5	/	2019	18.4	2013	4.2
	29.78	/	2024			4.5
Greece	4 (estimate)	/	2020	2.6	10/2015	8.7
	10	/	2050			3.9
Switzerland	1.5	Mainly LV	2016	1.2	2015	25
	1.8	Mainly LV	2017			22.5
	2.1	Mainly LV	2018			20.5
	12	Mainly LV	2050			6.8
ENTSO-E (solar gen.) [10]	104 (Conservative scenario A) 111 (Best Estimate scenario B)	/	2020	82.8	2014	3.9 5.
	125 (Conservative scenario A) 139 (Best Estimate scenario B)	/	2025			3.8 4.8
Japan	64	/	2030	23.3	2014	6.5
U.S.A.	≈100[16]	/	2021	18.3	2014	27.5

2.3.2 Other generation and demand

The Table 9 summarizes the evolution of other generation and demand. In the whole European area of ENTSO-E, two scenarios (*scenario A* and *scenario B*) have been defined for the evaluation of the risk for the security of supply over the coming years [10]. These scenarios, known as Scenario A “Conservative” and Scenario B “Best Estimate”, are based on national generation adequacy outlooks prepared by each individual TSO. The so called “conservative” scenario A takes into account: i) additional investments in generation or decommissioning with high certainty of happening; ii) the best estimate of load forecast available to the TSOs, taking into account the highest expected growth of the consumption according to national grid development plans; a RES evolution involving 105 GW of new capacity in period 2016-2025. The “Best Estimate” scenario B takes into account: i) the generation capacity evolution described in Scenario A as well as future power plants whose commissioning can be considered as reasonably credible by TSOs according to the available national information; ii) almost the same best estimation of load forecast used in scenario A (with some national exceptions); iii) a RES evolution involving 185 GW of new capacity in period 2016-2025.

Total or partial thermonuclear decommissioning may be expected in Belgium, Germany, Japan and Switzerland. The progressive decommissioning of thermal and thermonuclear power plants will be compensated by renewables like PV and wind off/on-shore. In Germany, the thermonuclear capacity should be replaced by wind, PV and other energy sources until the year 2022.

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[15] Scenario B Netzentwicklungsplan Strom 2014

[16] Source GTM Research / SEIA U.S. Solar Market Insight. Information available at https://www.seia.org/news/us-solar-market-set-grow-119-2016-installations-reach-16-gw.

Table 9: Evolution of other generation capacity and demand

Country	Category	Expected value	Hor. Year	Variation	Period
Belgium	Thermal [GW]	8	2020	0	2015-2020
	Thermonuclear [GW]	5.5	2020	-0.4	2015-2020
	Hydro [GW]	1.5	2020	1.4	2015-2020
	Wind on-shore [GW]	2.5	2020	2.3	2015-2020
	Wind off-shore [GW]	1.5	2020		
	Other generation [GW]	1.5	2020	/	/
	Yearly energy consumption [TWh]	96	2020	14.7	2012-2020
Germany[17]	Thermal [GW]	72.7 (fossil)	2024	-5.1	2012-2024
	Thermonuclear [GW]	0	2024	-12.1	2012-2024
	Hydro [GW]	4.8	2024	+0.4	2012-2024
	Wind on-shore [GW]	50.4	2024	+22.2	08/2014-2024
	Wind off-shore [GW]	12.8	2024		
	Other generation [GW]	12.6	2024		
	Yearly energy consumption [TWh]	535.2	2024		
Greece	Thermal [GW]	1.755	2020	-8.0	10/2015-2020
	Thermonuclear [GW]	0		0	
	Hydro [GW]	0.688	2020	-2.6	10/2015-2020
	Wind on-shore [GW]	7.500 (including off-shore)	2020	6.0	10/2015-2020
	Wind off-shore [GW]				
	Yearly energy consumption [TWh]	62	2020	11.3	2014-2024
Italy	Thermal [GW]	55	≈2020	-20.8	2013-2020
	Thermonuclear [GW]	0		0	
	Hydro [GW]	19	≈2024	4.5	2013-2024
	Wind on-shore [GW]	15	2024	7.2	2013-2024
	Wind off-shore [GW]	0.65	2024		
	Other generation [GW]	7.7 (biomass)	≈2024		
	Yearly energy consumption [TWh]	327	2024	-3	2013-2024
Switz.	Thermal [GW]	constant		/	/
	Thermonuclear [GW]	Possible phase out until 2034		/	/
	Hydro [GW]	constant		/	/
	Wind on-shore [GW]	marginal		/	/
	Wind off-shore [GW]	None		/	/
	Other generation [GW]	2 (CHP. rough estimation)	2050	/	/
	Yearly energy consumption [TWh]	60 (Should stay constant by means of more efficiency and increasing electrification)	2050	/	/
ENTSO-E [10]	Thermal [GW]	380; 344 (Conservative scenario A) 377; 365 (Best Estimate scenario B)	2020; 2025	-108.5 (A) -87.5 (B)	2014-2025
	Thermonuclear [GW]	119; 103 (Conservative scenario A) 121; 106 (Best Estimate scenario B)	2020; 2025	-23.5 (A) -20.5 (B)	2014-2025
	Hydro [GW]	159; 160 (Conservative scenario A) 162; 166 (Best Estimate scenario B)	2020; 2025	-42 (A) -36 (B)	2014-2025
	Wind [GW]	171; 197 (Conservative scenario A) 193; 255 (Best Estimate scenario B)	2020; 2025	74.2 (A) 132.2 (B)	2014-2025
	Yearly energy consumption [TWh]	/	2020; 2025	248 (B)	2016-2025
Japan	Thermal [GW]	87.80	2030	-106.1	2014-2030
	Thermonuclear [GW]	36.5	2030	-7.8	2014-2030
	Hydro [GW]	50.4	2030	0.8	2014-2030
	Wind on-shore [GW]	9.8	2030	7.8	2014-2030
	Wind off-shore [GW]	0.8	2030		
	Other generation [GW]	5.5	2030		
	Yearly energy consumption [TWh]	1065	2030	132	2014-2030

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[17] Scenario B 2024 Netzentwicklungsplan Strom 2014

2.4 Integration of PV forecast into power system operation and market

Solar forecasting in power system is quite recent: cloud movements and evolution/involution, and sometimes fog are the main reasons for PV generation volatility. Sky images are suitable to produce short-term forecasts, whereas satellite images can be used to anticipate radiation changes within a time horizon of few hours. Forecasting can reduce the uncertainty associated with PV as well wind or other renewable energy sources. Previous paragraph 2.3 showed how solar PV in the electric grid is steadily rising in various areas worldwide. The increasing penetration of solar power has to be integrated with the conventional power plants, which are still needed for ancillary services supply and energy supply where sufficient energy is not supplied by renewable generation. Solar power forecasting is therefore very important for operational planning because it has to ensure a low uncertainty around the forecasted operating point.
In particular, solar and other RES forecast is needed to assess the net load (i.e. *gross load – RES output*) hence the day-ahead unit commitment of conventional generation.

Forecasts should also be taken into account for the evaluation of balancing power reserve requirements: with a large amount of RES generation, probabilistic approaches for the assessment of the balancing reserve become more and more important. Indeed, probabilistic approaches instead of deterministic ones allow containing uneconomic over-estimation of reserve since they are aimed to assess a reserve requirement associated to a reasonable risk degree. In other words, probabilistic approaches cope with the most probable events and exclude the most unlikely extreme situations (e.g. sudden loss of the 100% installed capacity of RES in a given large control area). In particular, probabilistic methodologies lead to the assessment of the probability concerning a given imbalance between load and generation; the corresponding probability cumulative distribution function gives a needed balancing reserve associated with a reliability probabilistic level that is assumed lower than 100% (Figure 1)([11], [12]).

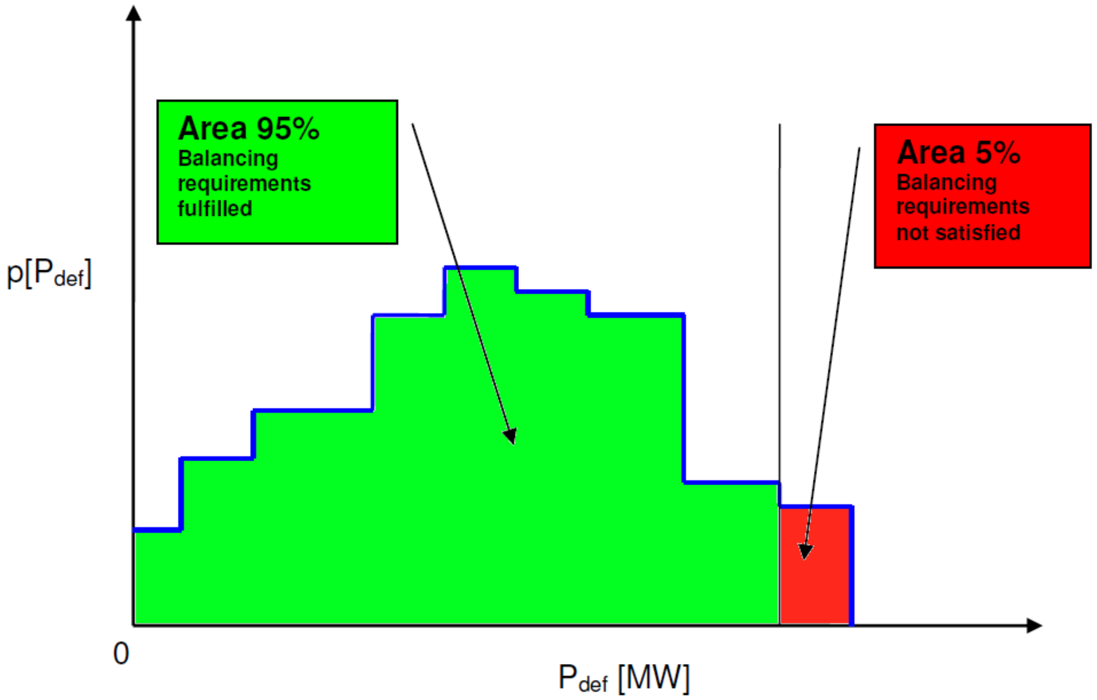

Figure 1: Example of discrete probability density function of possible power deficit P_{def} (source: [11])

PV forecast (**Table** 10) is used for system operation planning in almost all interviewed countries.

It is not used in Greece despite the not negligible installed capacity (2.6 GW and 2.4 GW only in mainland).

Table 10: PV forecast integration into power system operation and market

	Belgium	**Germany**	**Greece**	**Italy**	**Switzerland**	**Japan**
PV forecast used in operation planning	■	■	X	■	■	■
PV forecast used to assess day-ahead net load	■	■	X	■	n.a.	■
PV forecast used to assess generation unit commitment	■	■	X	■	n.a.	■
PV forecast used to assess power reserve	X	X	X	■	n.a.	■

(■: adopted x: not adopted n.a.: info not available)

In Belgium, market players provide forecasts to TSO that carries out operation planning.

The publicly-owned company[18] which promotes and supports RES in Italy, supplies small PV (< 10MVA) forecasts to the Italian TSO with the aim to optimize dispatching volumes. The TSO takes into account, in the programming phase, the above forecasts and implements its own PV generation forecast on the basis of solar radiation, temperature, installed PV and the latest available meteorological forecast ([13], [14]).

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[18] See footnote .

In Japan, it has been recently changed that regulated transmission and distribution companies, as a last resort, have to purchase PV energy from PV generation owners on the basis of uncertainty of PV energy in each Vertical Integrated Utilities (VIU) control area.

Italy and Japan use PV forecast for the assessment of power reserve (Table 11). In Italy, RES forecast is used to assess the tertiary reserve for balancing uncertainties around a forecasted operating point, due to RES and load deviations in addition to forced outages of conventional programmable generation. In Japan PV forecast is used for assessment of the hot (spinning) reserve.

Table 11: Specifications about PV forecast integrated into power system operation and market

		Belgium	**Germany**	**Italy**	**Japan**
PV forecast used to assess ahead net load (gross load – RES output)	**Context**	Day-ahead and intraday energy market	Day-ahead and intraday energy market	Day-ahead energy market	Two days before obligation in balancing rule
	Time resolution	1h (15 min settlement)	15 min	1h	30 min
	Maximum time horizon	12-36h (day-ahead); 5min (intraday)	up to 3 days	day-ahead	day-ahead
PV forecast used to assess generation unit commitment	**Context**	Forward, Day-ahead and intraday markets	Day-ahead energy market	Day ahead energy market	Two days before obligation in balancing rule
	Time resolution		15 min	1h	1 h
	Maximum time horizon		Several days	day-ahead	1 week, 2 days[19]
PV forecast used to assess power reserve	**Context**	Not used	Not used	Day-ahead and intraday dispatching services market	Day-ahead forecast of supply and demand in system operator
	Time resolution			1h (15 min settlement)	1 h
	Maximum time horizon			day-ahead	
	Kind of reserve			tertiary reserve	hot reserve

2.5 Operational events experienced with presence of PV into power system

It is well known that, on 20 March 2015, a solar eclipse took place in Europe involving a significant PV output decrease ([15]). That involved a true stress test for pan-European systems where different measures were successfully implemented by TSOs around Europe ([16]):

- higher operating reserves allocation (various TSOs);

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[19] One week for pumped storage operation planning, 2 days for whole sale market.

- specific control logics implemented for reserve activation during the solar eclipse (German TSOs);
- cross-border NTC[20] reduction (Italian TSO);
- HVDC link capacity reduction up to 50% (links between Northern Europe, UK, and CE);
- preventive decrease, in Italy, of PV power production, implemented in order to limit power dip and to have enough regulating capacity (4400 MW, around 25% of Italian PV capacity, was put out of service from 7 a.m. to 2 p.m.).

The above and other measures allowed keeping frequency within the acceptable range of ± 50 mHz ([16]).

In the US a total solar eclipse occurred on August 21, 2017. A significant impact on the power system was expected however, similarly to the case of Europe in 2015, the event was less dramatic than expected because of cloudy weather and changes to customer behavior related to the eclipse. For instance, California had expected utility-scale solar output to drop by 4,200 MW during the event, but the actual drop was of only 3,400 MW. Similarly, PJM Interconnection experienced a net decrease in demand of about 5,000 MW throughout the eclipse, for a variety of factors. In any case a solar eclipse is a real challenge for a power system largely reliant on PV generation and it is expected that similar events will bring more impact in future as PV penetration increases.

The eclipse is more challenging since it involves huge variations of the solar infeed, first downward and then upward, quite fast compared to the capabilities of the conventional generating units.

Overall, an eclipse represents a rare event. Other concerns, correlated to presence of PV into power systems, are instead ordinarily faced by all the interviewed countries. These concerns are related to: i) PV output uncertainty and variability; ii) ability of network, at HV level, to accommodate possible high power flows due to PV output; iii) PV tripping due to interface protections in case of emergency operation, especially in case of old protection settings with very narrow frequency range for PV operation. While the first two items still represent big challenges, new protection settings are, in general, adopted with larger frequency ranges and retrofitting programs have been implemented on the basis of PV plant rated power, date and voltage level of connection [18].

In addition to the above issues, the progressive decommissioning of low competitive traditional generation involves: system inertia reduction with lower inertial response in case of frequency perturbations; lower operating power reserve; lower short circuit level with more relevant voltage dips in case of short circuits on transmission HV level (short circuit current "I_{SC}" of PV is around 1,1 × I_{rated} against a I_{SC} of about 5 × I_{rated} in case of synchronous generators).

Another possible concern consists in the changes in daily profile of net load. In case of high PV penetration, the lower net load in central day light hours involves the risk of

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[20] Net transfer Capacity: the NET TRANSFER CAPACITY is the maximum total exchange program between two adjacent control areas compatible with security standards applicable in all control areas and taking into account the technical uncertainties on future network conditions.

overgeneration since a minimum amount of traditional generation is required for operational security (e.g. balancing reserve). In the evening, the decreasing PV output involves higher upward ramps of net load with consequent risk of slow system response to load ramp.

Belgium and Germany

PV output deviations from expected forecast (e.g. due to fog/low stratus) can assume relevant values, if compared with power system regulating capacity, in Germany and Belgium. In particular forecast error may involve power shortage in case of fog and low clouds involving a high sky covering.

In Germany the amount of PV shortage, due to forecast errors, may be in the order of several GWs, for several hours.

In Belgium voltage problems on the distribution level can result in the disconnection of DG equipment.

RES curtailment, in order to relief transmission lines, is a periodic practice in Germany but it is mainly performed because and on wind generation.

Greece

Small amount of PV power shortage can occur in Greece because of voltage dips at distribution level. Shortage duration is usually of minutes. In case of frequent events, the window of voltage operation is changed for the affected grid segment.

Italy

In Italy, even if most of PV capacity is installed on distribution level, the aggregated high volumes of PV production impact of HV and EHV transmission grid, especially in areas with low local demand. Power reversal, from MV to HV level, was observed for the 5% of yearly hours (y. 2015) in 793 HV/MV primary substations ([19]), involving possible congestions at HV and up to EHV level (>200 kV) with consequent establishment of different market zones and different clearing prices involving lower global efficiency of energy market results in comparison to a unique clearing price. Congestions are, in particular, highlighted in the south and in the Sicily and Sardinia island where the highest share of RES capacity is installed and where transmission capacity is lower due to the weakly meshed topology of the grid.

Of particular interest is the system operational security of the two main islands, namely Sicily and Sardinia. On May 18th 2011, Sicily was affected by the tripping of 200 MW PV generated power due to old protection frequency settings ($49.7 \leq f \leq 50.3$Hz), after the outage of a conventional thermal plant (150 MW). These events involved load shedding due to under-frequency and pointed out the need of larger frequency ranges for PV operation. At present, large frequency ranges for new PV plants and retrofitting programs have been adopted. Traditional generation displacement is a significant issue for security of power system operation in the Sardinia island, asynchronously interconnected to mainland with two HVDC systems: the old LCC[21] HVDC 300 MW SA.CO.I.[22] and the newer LCC 2x500 MW SA.PE.I.[23]. The expected refurbishment or SA.CO.I is being evaluated with adoption of VSC converter technology in order to overcome possible limits due to the minimum short circuit level on power system and to support voltage regulation.

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[21] Line Commutated Converter.

[22] SArdina – COrsica – Italian peninsula three-terminal monopolar HVDC.

[23] SArdina – Italian PEninsula two-terminal bipolar HVDC.

Concerning the daily profile of net load, Figure 2 depicts the Italian gross and net load evolution in the working days of March, comparing the years 2011 and 2013: while the gross load is almost unchanged, it can be seen how the net load changes as consequence of the PV capacity ([19]) increase from 2011 (12.8 GW) to 2013 (18.4 GW). In order to face the daily net load steeper ramps, faster switch-on/off cycles of traditional thermal generation are required in addition to the improvement of regulating power ramps.

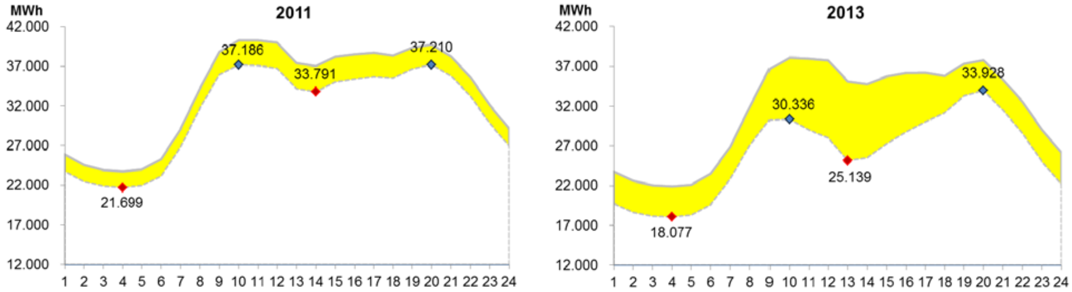

Figure 2: Net and gross load profile evolution in the working days of March in Italy (source AEEGSI [20])

Japan

In Japan, large amount of PV deployment is unevenly going on over 10 balancing areas. In Kyushu, one of the balancing areas, it is expected to make PV generation curtailment due to overgeneration in terms of demand supply balance as a total area in the near future, dependent on the power demand, base load generation, and interconnection capacity.

2.6 PV requirements in case of frequency and voltage deviations

This paragraph summarizes the requirements in terms of PV range of operation, in the interviewed countries, with the aim to help the definition of the consequences of possible large perturbations occurring on power system and interacting with PV protections.

Larger frequency operational ranges are in general required, in comparison with the past, by recent developments of national grid codes and, in some cases, a certain frequency droop control is required if over-frequency occurs.

Table 12 summarizes the main requirements in terms of frequency and voltage ranges of operation, respectively for PV on LV, MV and HV voltage levels. It can be noted that:

- in Japan, no underfrequency range is required for PV operation at all voltage levels;
- in Greek, despite the general change, quite stringent frequency limits for PV operation in mainland (on all LV, MV, HV levels): 49.5- 50.5Hz is adopted;
- LVRT[24] capabilities are in general required for PV at MV and HV voltage levels;
- on LV level LVRT is required in Italy, on the basis of the rated size, and Japan while it is under discussion in Germany.

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[24] Low Voltage Ride Through “LVRT” is the capability of electric generators to stay connected in short periods with low voltage, e.g. residual voltage in case of voltage dips due to short circuits. It is needed to avoid a widespread loss of generation in case of short circuit, on HV or EHV levels.

Table 12: LV level PV requirements in case of voltage and frequency deviations

	PV size [kW]	Voltage range V_{min}÷V_{max} [% of $V_{nominal}$]	LVRT capability (Yes/no)	Frequency range fmin÷fmax ensured [Hz]	Frequency droop (Yes/No)	Year of connection
Belgium	5	+/-15%	No (within 0.2 sec)	47-51	No	/
Germany	all	+/- 10%, -15% +10% (depending on time interval & probability acc. EN50160)	No	47.7-51.5	Yes ΔP=40% P_M pro Hz ([21])	From 2012
Greece	≤100 Mainland	-20% +15%	No	49.5-50.5	No	
	≤100 Autonomous Power Systems (Islands)	-20% +15%		47.5 - 51.5		
Italy ([22],[23])	$P_N \geq 1$ kW	-15% +10%	No	$49 \leq f \leq 51$		From 01/04/2012 to 30/06/2012
	$P_N \geq 1$ kW	-15% +10%	No	$47.5 \leq f \leq 51.5$	No	From 01/07/2012 to 31/12/2012
	$P_N \geq 1$ kW	-15% +10%	No	$47.5 \leq f \leq 51.5$	Yes 2.4%P_{inj} in the over-frequency range $50.3 \leq f \leq 51.5$Hz	After 31/12/2012
	$A_N \geq 6$ kVA	-15% +10%	Yes (see Figure 4)	$47.5 \leq f \leq 51.5$	Yes 2.4%P_{inj} in the over-frequency range $50.3 \leq f \leq 51.5$Hz	After 31/12/2012
	$6 \leq P_N \leq 20$kW (retrofitting)	-15% +10%		$49 \leq f \leq 51$		Before 01/04/2012
Switz.	Same as in Germany (EN50160)					
Japan	< 50kW	95 – 107 [V] 182 – 222 [V]	Yes Voltage dip amplitude: over 80% of rated value Duration time: 1s	50.0 +0.8,-0 60.0 +1.0,-0	Yes (Step Shape) 0.8Hz for 50Hz 1.0Hz for 60Hz (Ramp Shape) 47.5-51.5 Hz for 50Hz 57.0-61.8 Hz for 60Hz	

Table 13: MV level PV requirements in case of voltage and frequency deviations

	PV size [kW]	Voltage range V_{min}÷V_{max} [% of $V_{nominal}$]	LVRT capability YES/NO	Frequency range f_{min}÷f_{max} ensured [Hz]	Frequency droop	Year of connection
Belgium	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.
Germany	All	+/- 10%, +/- 15% (depending on time interval & probability acc. EN50160)	Yes (see Figure 3)	47.5-51.5 (suggested setting BDEW MS-RL; [24])	Yes - Compare LV	From 2009
Greece	100 to ~5MWp	-15% +10% (but also depending on local conditions)	No	49.5- 50.5	No	
	Autonomous Power Systems (Islands)	-15% +10% (but also depending on local conditions)		47.5- 51.5		
Italy ([23])	P_N≥1 kW	-15% +10%	No	47.5≤f≤51.5 (in case of transients due to HV level) 49.7≤f≤50.3 (in case of transients due to MV level)	No	From 01/04/2012 to 30/06/2012
	P_N≥1 kW	-15% +10%	No	47.5≤f≤51.5 (in case of transients due to HV level) 49.7≤f≤50.3 (in case of transients due to MV level)	Yes 2.4%P_{inj} (in the over-freq. range 50.3≤f≤51.5Hz)	From 01/07/2012
	A_N≥6 kVA	-15% +10%	Yes (see Figure 4)	47.5≤f≤51.5 (in case of transients due to HV level) 49.7≤f≤50.3 (in case of transients due to MV level)	Yes 2.4%P_{inj} (in the over-freq. range 50.3≤f≤51.5Hz)	From 01/07/2012
	P_N≤50 kW (retrofitting)	-15% +10%	No	49≤f≤51	No	Before 01/04/2012
	P_N≥50 kW (retrofitting)	-15% +10%	No	47.5≤f≤51.5 (in case of transients due to HV level) 49.7≤f≤50.3 (in case of transients due to MV level)	No	Before 01/04/2012
Japan	50kW-2MW	Maintain the LV voltage at regulated range	Same as for LV	Same as for LV	Same as for LV	

Table 14: HV level PV requirements in case of voltage and frequency deviations

	PV size [kW]	Voltage range $V_{min}÷V_{max}$ [% of $V_{nominal}$]	LVRT capability YES/NO	Frequency range $f_{min}÷f_{max}$ ensured [Hz]	Frequency droop	Year of connection
Belgium	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.
Germany	All	-	Yes	47.5-51.5 Hz (suggested setting VDE AR-N 4120; [25])	Yes Compare LV	
Greece	>5MWp	-15% +10%	No	49.5- 50.5	No	
Italy([27])	All	-15% +10%	Yes (see Figure 5)	47.5≤f≤51.5	Yes 2.4%P_{inj} (in the freq. range 50.3≤f≤51.5Hz)	
Japan	>2MW	Maintain the LV voltage at regulated range	Same as for LV	Same as for LV	Same as for LV	

2.6.1 *Germany*

Figure 3 depicts the LVRT capability required to PV on MV level: different schemes for tripping are foreseen on the basis of amplitude of voltage dip and time duration. In all cases, a 100% voltage dip (i.e. null residual voltage) has to be tolerated for, at least, 150 ms.

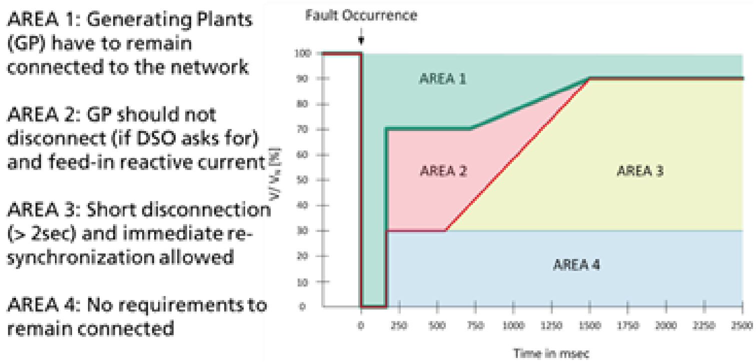

Figure 3: LVRT capability – MV level PV; Germany (According to [24])

2.6.2 *Italy*

In Italy, a 100% voltage dip has to be overcome without tripping respectively for:

- at least 200 ms, in case of PV plants with rated power P_{rated}≥6kVA and connected to distribution MV and LV level (Figure 4);
- at least 150 ms, in case of PV plants connected to transmission HV and EHV levels (Figure 5).

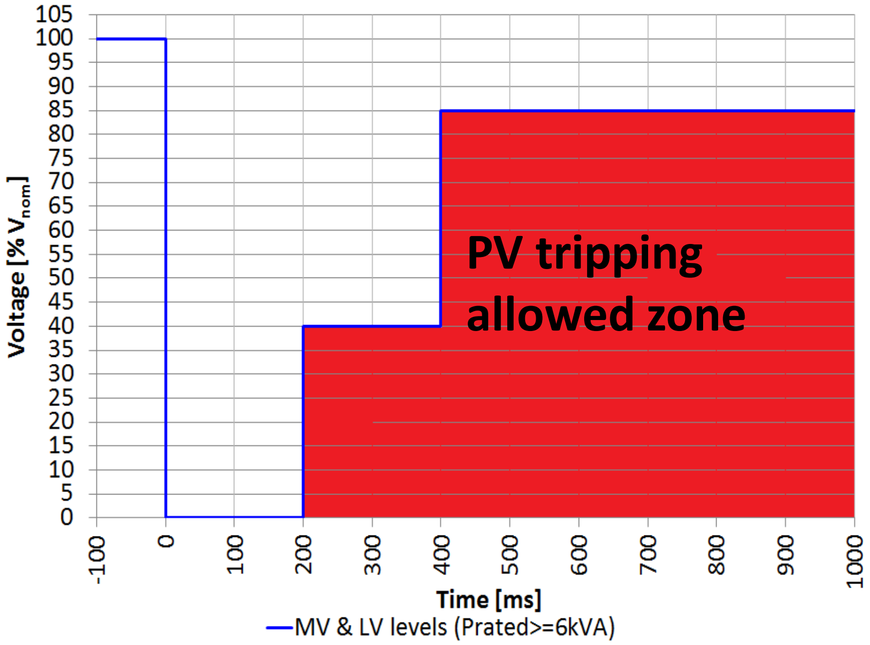

Figure 4: LVRT capability – MV and LV levels PV (P_{rated}≥6kVA); Italy (graphic based on [26])

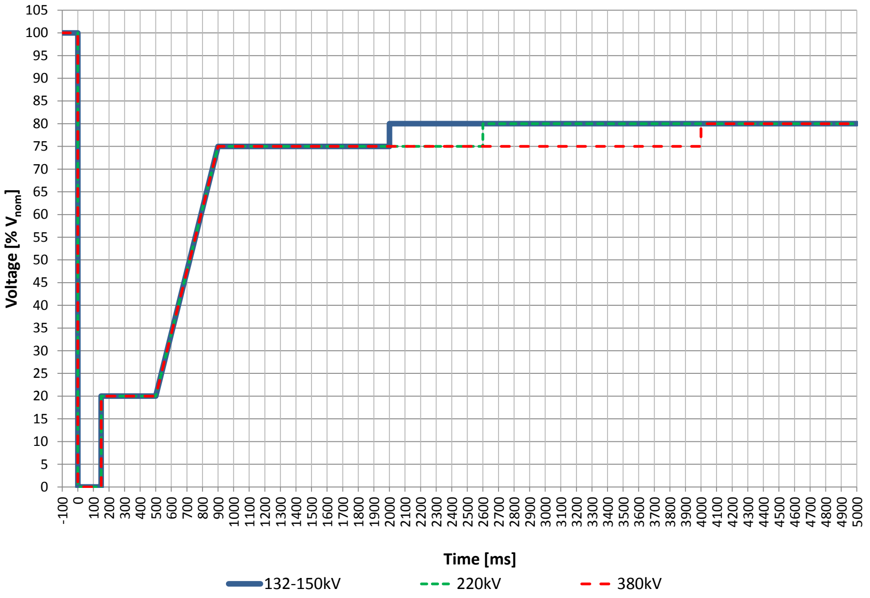

Figure 5: LVRT capability – HV level PV; Italy (graphic based on [27])

Concerning frequency relays protection, islanding operation of distribution grid must be avoided. Therefore protections of MV level PV have to distinguish between the fast frequency perturbations, due to distribution grid islanding or faults, and the usually slow frequency deviations due to perturbations at transmission level. In case of fast frequency variations, the narrow operational range "$49.7 \leq f \leq 50.3$" has to be enabled while, in case of slow variations, the larger range "$47.5 \leq f \leq 51.5$" has to be ensured.

Without remote signals, the activation of the narrow range (faults on MV level) can be triggered by means of one of the following functions:

- maximum homopolar voltage V_0 for detection of short circuits "phase-ground";
- maximum inverse sequence voltage V_i for detection of two-phase short circuits insulated from ground;
- maximum direct sequence voltage V_d for detection of three-phase or two-phase short circuits insulated from ground.

The above logic is represented in Figure 6.

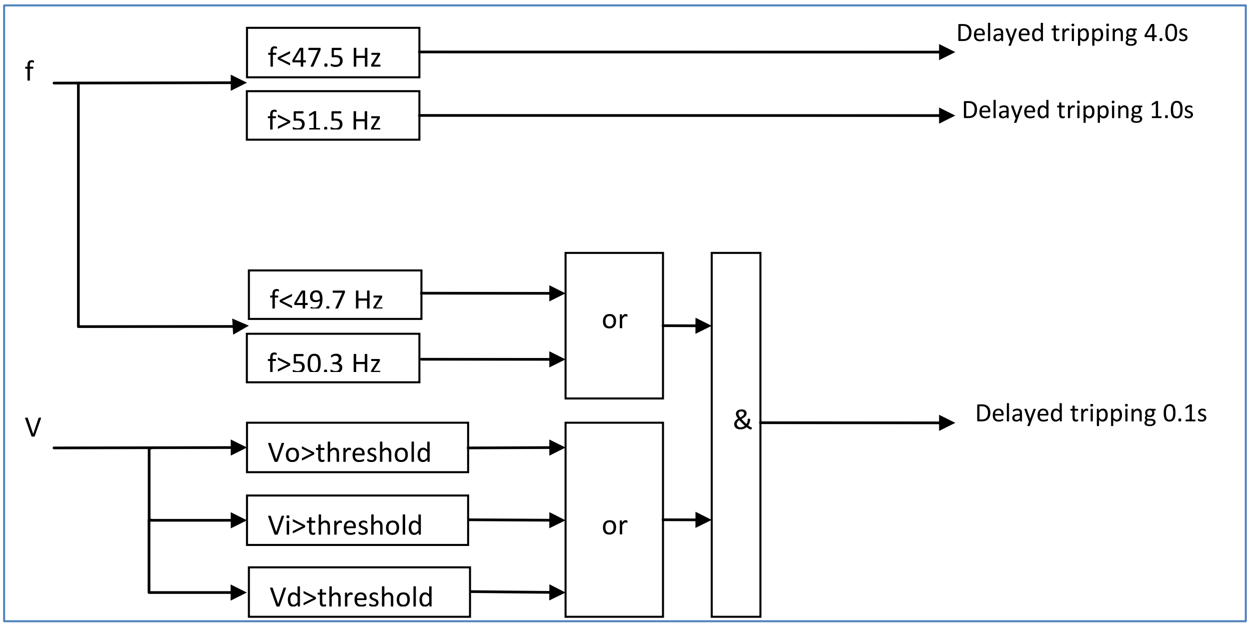

Figure 6: Logical scheme for activation of frequency relays with unblocking based on voltage; MV level PV - Italy (scheme based on [26])

The following Figure 7 depicts a possible logical schemes also based on remote signals ([26], [28]).

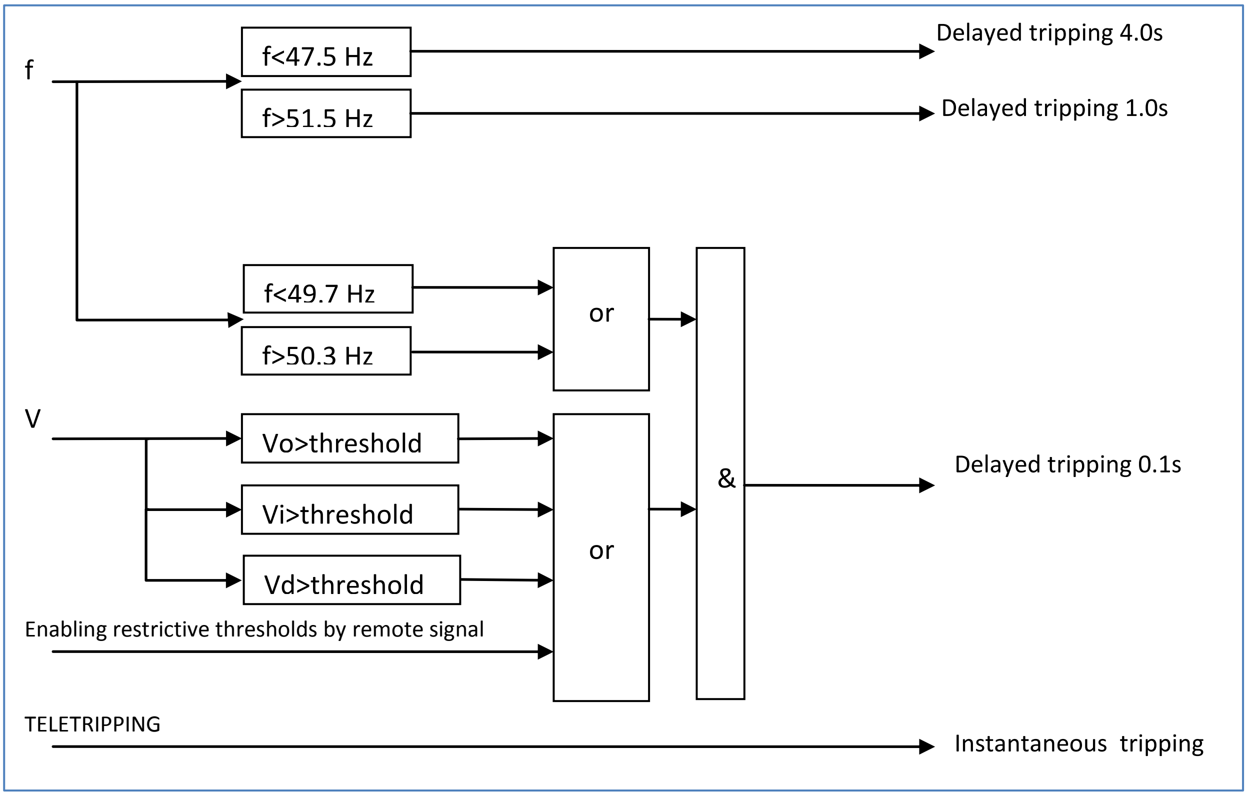

Figure 7: Logical scheme for activation of frequency relays with voltage unblocking, tripping and enabling of restrictive thresholds from remote. MV level PV - Italy (scheme based on [26], [28])

In case of LV level PV, the required frequency range is only the largest one“$47.5 \leq f \leq 51.5$” since needs of the global system are considered predominant in comparison with the local distribution grid ones. That is allowed because of the static nature of PV: indeed, unlike the rotating machines, no torsional torques may occur, even if an asynchronous re-closure on MV level is operated after a local fault.

3 Existing flexibility resources

Highly performant ancillary services are gaining more and more importance as the penetration of RES is increasing in the power system. In particular, high penetration of PV may lead to an increase in needed operating reserves since the system must be prepared for any sudden PV output fluctuations, on the basis of solar irradiance and clearness sky condition. Moreover, progressive traditional generation displacement, because of higher RES competitiveness or priority of dispatch, involves lower flexibility in terms of lower power reserve, lower system inertia (higher frequency fluctuations) and lower short circuit power (lower voltage support).

This chapter collects the survey results about the present status of flexibility resources and of the national practices about the operation power reserves. The aim is to supply proper information for analyses and simulations to be performed in PV integration studies.

3.1 Situation of flexibility resources

Table 15 shows the flexibility resources adopted, in the interviewed countries, in order to balance demand and generation; they are, in general, market regulated with the exception of Japan.

Table 15: Flexibility resources adopted for power balancing

	Belgium	**Switz.**	**Germany**	**Greece**	**Italy**	**Japan**
Open Cycle Gas Turbine (OCGT)	■	■	■	■	■	X
Combined Cycle Gas Turbine (CCGT)	■	■	■	■	■	■
Conventional thermal p.p.	■	■	■	■	■	■
Hydro Power Plant	X	■	■	■	■	■
Hydro Pumped Storage	■	■	■	■	■	■
Interruptible load	■	X	■	■	■	X
Battery storage for frequency control	X	■ Pilot project	■	X	■ Pilot projects	■ Pilot projects
Interconnections for primary FCR capacity sharing	■	■ FACTS	■ FACTS HVDC	■ HVDC	■ HVDC	■ FACTS HVDC
Regulation scheme	■ market & bilateral agreements with TSO/ISO	■ market	■ market	■ market	■ market & bilateral agreements with TSO/ISO	■ managed by VIUs/TSOs

(■: adopted   x: not adopted)

Conventional dispatchable power generation plants are a traditional source of flexibility even if, in some cases (e.g. thermal), performances improvement is recommended.

Battery storage is instead at early stages. In Italy, two pilot projects[25] have been set up: i) the so-called "Energy-Intensive" project involving 35 MW of storage systems installed in mainland, whose first aim is to reduce the curtailment of wind generation due to sub-transmission grid constraints, incrementing the transmission grid's capacity to absorb RES output; ii) the so-called "Power-Intensive" projects involving the installation of 2 x 8 MW batteries in the two major Italian islands with the aim to improve security of operation, supplying Frequency Containment Reserve (e.g. with Fast Frequency Responses [29]).

Information about the main performances of flexible generation is shown in Table 16 and in Table 17. Changes in solar irradiance may occur in short timescales therefore conventional generators have to be capable of changing their output quickly with large

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[25] Info available at web address: https://www.terna.it/en-gb/azienda/chisiamo/ternastorage.aspx.

ramp rates. Moreover, the PV output changes the typical daily net load profile involving the need for frequent switch-on/switch-off cycles of conventional generation. Thermal power plants, in general, have to stay in operation for at least some hours because of thermal dynamics. The lower the minimum duration of continuous operation, the higher the number of switch-on/switch-off cycles for a given time interval (e.g. daily 24 hours).

Table 16: Main typical performances of nuclear and fossil-fuelled power plants

	Type	**Start-up time [h]**	**Minimum time period of continuous operation [H]**	**Power ramping gradients [MW/min]**	**Power ramping gradients [%/min]**	**Technical minimum**
Belgium	Conventional thermal p.p.	6	6	--	3	--
	OCGT	0.2	0	--	10	--
	CCGT	1	4	--	6	--
	Nuclear	24	24	--	2	--
Italy [30]	Conventional thermal (e.g. steam turbine)	16	12 (almost plants)	2 (average)	--	--
	OCGT	--	--	7 (average)	--	--
	CCGT	5	<12 (39% of plants) <4 (14% of plants) <1 (2% of plants)	14 (average) (P_{rated}=320/350MW) 40 (max for only 3 plants)	--	--
Japan[26]	Conventional thermal (e.g. steam turbine) USC[27] coal plant 600 - 1,000MW	over 4	--	--	3%	--
	OCGT		--	--		--
	CCGT 1.100 – 1.500°C	2 - 3	--	--	5%	--
IEA (y.2014) [31]	Nuclear	--	--	--	0.3÷5	40÷100%
	Coal	2 - 7	--	--	0.6÷8	20÷60%
	Lignite	2 - 8	--	--	0.6÷6	40÷60%
	Combined Cycle Gas	1 - 4	--	--	0.8÷15	15÷50%

It is worth reminding that the highest reliability in forecast can be achieved in the short-term. However, looking at the above start-up time of the nuclear and fossil fuelled power plants, a short-term forecasting may be useless if the time needed for activation of

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[26] Report of Thermal and Nuclear Power Engineering Society. Info at web address: https://www.tenpes.or.jp/en/publication/index.html.

[27] Ultra SuperCritical. USC steam generation involves higher steam cycle efficiency since a USC unit operates above supercritical pressure with high temperatures (around 600°C).

the available flexibility resources may amount to some hours. In other words, the above plants cannot be used to cope with RES forecast short-term updates if they are off. Short-term time horizon for the operational planning is suitable for dispatching quick-start generators, e.g. pumped storage hydro power plants, latest generation combined cycles or open cycle gas turbines).

Table 17: Main typical performances of typical hydro power plants and pumped storage

	Type	Start-up time	Power ramping gradients
Belgium	Hydro power plants	--	--
	Hydro pumped storage	1 min	1000 [MW/min]
Italy [30]	Hydro power plants	--	18 (average) [MW/min]
	Hydro pumped storage	--	187 (average) [MW/min]
IEA (y.2014) [31]	Reservoir hydro	--	15-25 [%/min]

3.2 National practice about operating power reserves

One of the most important ancillary services is maintaining the frequency within the given margins by continuous modulation of active power. This capacity can be defined as Operating Reserve ([32]) or Control Reserves ([33]) (or Operational Reserve; [34]).

Power unbalances may occur on different time scales, from seconds to days, and different control strategies may be required depending on the speed of the variability. A general way of classifying operating reserves could be based on whether they are deployed during normal conditions or event conditions (e.g. tripping of a generator or load). Indeed, the frequency then must be corrected back to its scheduled setting and the system's ACE (Area Control Error) must be reduced to zero during both instantaneous and non-instantaneous events. A certain amount of replacement reserves has then to be allocated in order to protect the system against possible further contingencies.

Standards about operating reserve are generally based on certain reliability criteria and allowable risk criteria, but often differ, sometimes substantially, from balancing area to balancing area. The following Operating Reserve classification will be based on definitions used in North America and in Europe, specifically looking at the North American Electric Reliability Corporation (NERC; [32]) and the European Network of Transmission System Operators (ENTSO-E; [33], [34]).

NERC standards distinguish Operating Reserves under normal and contingency conditions. Under normal conditions:

- **regulating reserves**: online resources, on Automatic Generation Control (AGC), that respond for upward and downward power activation aimed to compensate minute-to-minute power fluctuations.
- **load following (or fast energy markets)**: similar to regulating reserves but slower. Bridges between the regulation service and the hourly or sub-hourly energy markets.

Under contingency conditions:

- **spinning reserve**: online generation, synchronized to the grid, that can begin to increase output immediately in response to a frequency change in case of relevant generator or transmission outage and can reach full output within few minutes to comply with NERC's Disturbance Control Standard (e.g. 10 minutes)

- **non spinning reserve**: same as spinning reserve but not immediate initial response; resources can be offline but still must be capable of reaching full output within few minutes.

- **replacement reserves**: reserve is used to restore spinning and non-spinning reserves to their pre-contingency status; response time in tens of minutes (e.g. 30-60 min).

ENTSO-E standards distinguish for Continental Europe (CE) the Control Reserve:

- **Primary Control Reserve** (**Frequency Containment Reserve FCR**) - The primary control reserve is the (positive/negative) part of the primary control range measured from the working point prior to the disturbance up to the maximum primary control power. The primary control range is the range of adjustment of primary control power, within which primary controllers can provide automatic control, in both directions (upward/downward), in response to a frequency deviation (time fame activation within seconds)

- **Secondary Control Reserve** (**automatic Frequency Restoration Reserve aFRR**) - The positive/negative secondary control reserve is the part of the secondary control range between the working point and the maximum / minimum value. The secondary control range is the range of adjustment of the secondary control power, within which the secondary controller can operate automatically, in both directions at the time concerned. Secondary control aims to keep or to restore the power balance in each control area and, consequently, to keep or to restore the system frequency to its set-point value (e.g. 50 Hz) and the power interchanges with adjacent control areas to their programmed scheduled values, thus ensuring that the full reserve of primary control power activated will be made available again. These actions of secondary control will take place simultaneously and continually, both in response to minor deviations (inevitable occurrences during normal operation) and in response to a major discrepancy between production and consumption (e.g. tripping of a generator or network disconnection).

- **Tertiary Control Reserve** (**manual Frequency Restoration Reserve mFRR**) - The power which can be connected (automatically or manually) under tertiary control, in order to provide an adequate secondary control reserve. This reserve must be used in such a way that it will contribute to the restoration of the secondary control range when required. The restoration of an adequate secondary control range may take, for example, up to 15 minutes, whereas tertiary control for the optimization of the network and generating system will not necessarily be complete after this time.

3.2.1 Reserve requirements

This section is focused on general requirements by TSO/ISO about operating reserves.

Detailed information on the whole pan European system is available on ENTSO-E website ([35], [36]).

In particular Table 18, Table 19 and Table 20 synthesize the information supplied by the interviewed countries. Even if it is not complete and restricted to interviewed countries, this information provides support for system adequacy evaluation, in terms of availability of proper reserve margins, and dynamic analysis of power systems (e.g. TSA in case of large perturbations with consequent power reserve deployment).

Procurement and payments schemes for operating reserve are summarized in Table 21.

Table 18: Present national requirements about primary reserve (FCR)

	Belgium	Germany	Italy	Switzerland	Japan
Provider	generators & demand	generators & demand	generators	generators (demand could, normally doesn't)	Generators
Minimum allowed rated power of participating units	None	1MW per pool	10 MVA	1 MW	--
Permanent frequency droop	adopted	--	Adopted (5% thermal, 4% hydro,2.4wind and PV downward)	2-12%	--
Reserve deployment Time	1/2 of reserve within 15 sec; whole reserve within 30 sec	30s	1/2 of reserve within 15 sec; whole reserve within 30 sec	2-15/30s	--
Minimum frequency deviation for control activation (e.g. deviation beyond a dead band)	100 mHz	±20mHz	±20 mHz	0 to 500 mHz	--
Minimum ramp rate	--	200%Reserve/min	3%Pnom/min		--
Minimum reserve time duration	15 minutes		15 minutes	15-30 minutes	--
Time distance between reserve allocation and real time	day-ahead	about 6 till 13 days	from hours ahead to day-ahead	--	--
Reserve margin allocated	--	--	1.5% Pnom	--	--

Table 19: Present national requirements about secondary reserve (aFRR)

	Belgium	Germany	Italy	Switzerland	Japan
Provider	Generators and Demand, Pumped Storage	Generators and Demand	Generators	Generators (ongoing projects for Demand)	Generators
Minimum allowed rated power of participating units	5 MW	5 MW per pool	10MVA	5 MW	---
Reserve deployment Time	30 sec to 15 minutes	300 sec	sec to 15 minutes	---	---
Activation	Automatic	Automatic	Automatic	Automatic	---
Minimum ramp rate	Fully available after 30 seconds	20%Prated/min	1%Reservemargin / 2sec	---	---
Minimum reserve time duration	15 min	none	2 h	---	---
Time distance between reserve allocation and real time	day-ahead	about 6 till 13 days	from hours ahead to day-ahead	weekly auctions	---

Table 20: Present national requirements about tertiary reserve (mFRR)

	Belgium	Germany	Italy	Switzerland	Japan
Provider	Generators and Demand and Pumped Storage, (also Distribution level)	Generators and Demand	Generators	Generators	Generators
Minimum allowed rated power of participating units	None	5 MW per pool	10MVA	5 MW	--
Reserve deployment Time	15 min for R3-PROD (conventional production), 3 minutes for R3DP (demand response)	15 min	15min for replacement of secondary reserve or 120min for balancing load, RES, and forced outages of conventional generation	tender blocks of 4h (bids must fit into such a block)	--
Activation	Manual	Manual	Manual	Manual	--
Minimum ramp rate	Full delivery in 15 minutes	6.6% [%Prated/min] coming from the deployment time	10 MW/15min or 50MW/min gradient in case of secondary reserve replacement.	no ramps for tertiary control	--
Minimum reserve time duration	No minimum, but maximum of 8 hours (R3-PROD), maximum 4 or 8 hours (R3DP)	15 min	No minimum, with exception of 4 h for reservoir hydro power plants	within a 4h tender blocks	--
Time resolution for the margin allocation	--	4 hours	1 hour	15 min	--
Time distance between margin allocation and real time	day-ahead	day-ahead till days ahead	from hours ahead to day-ahead	--	--

Table 21: National procurement/payment roles for operating reserves

	Primary reserve (FCR)	Non-spinning reserve or secondary reserve (aFRR)	Replacement reserve or tertiary reserve (mFRR)
Belgium	Monthly tender/reservation price €/MW	Tenders & reservations free bids/ reservation price €/MW and capped activation price €/MWh free activation price €/MWh	Tenders & reservations free bids/ reservation price €/MW and capped activation price €/MWh free activation price €/MWh
Germany	org. Market/pay as bid/uplift component in final energy price for consumer (network tariff)	org. Market/pay as bid/capacity costs paid by consumers (network tariff).	org. Market/pay as bid/costs paid by consumers "uplift". Capacity costs paid by consumers, activation costs paid by unbalancing responsible parties.
Italy	Mandatory provision with fixed %Prated of committed units Not remunerated, unless ad-hoc meters installed Cost recovery scheme: paid by consumers within the "uplift" component of the final energy price	Procurement scheme: Organized Market Payment rule: Pay as bid Cost recovery scheme: paid by consumers within the "uplift" component of the final energy price	Procurement scheme: Organized Market Payment rule: Pay as bid Cost recovery scheme: paid by consumers within the "uplift" component of the final energy price
Switzerland	org. Market/pay as bid (energy is not compensated)/paid by consumer within the "uplift" component on final energy price	org. Market (volume defined by TSO, approx. 400MW/pay as bid/paid by consumer within the "uplift" component on final energy price	org. Market/pay as bid/paid by consumer within the "uplift" component on final energy price
Japan	Basically, each VIU procures each reserve by the integral operation of own generation and transmission sections	Basically, each VIU procures each reserve by the integral operation of own generation and transmission sections	Basically, each VIU procures each reserve by the integral operation of own generation and transmission sections

4 Innovative flexibility resources including demand response

Changes of PV output span in a wide range of timescales with consequent different kind of impact on the power system: i) seconds/minutes with impact on power quality, power reserve and load following; ii) hours/days with impact on unit commitment. The expected matters for operation, in the interviewed countries, are shown in Table 22.

Table 22: elements affected by PV evolution in the interviewed countries

	Belgium	Germany	Italy	Japan
V control at distribution Level	■	■	■	■
Frequency control (Balancing) at Transmission Level	■	■	■	■
Balancing in interaction between transmission and distribution	■		■	
V control in interaction between transmission and distribution	■	■	■	

Looking at the above PV impacts on power system, it is necessary to identify new highly performant flexibility resources, which are quickly available if needed, such as demand response. This latter, in addition to remote controlled output modification of distributed generation (hereinafter, DG output modification), involves the need of smart grids based on ICT infrastructures allowing observability and controllability of the grid, also at distribution level. ICT is needed to help system operation performed by TSOs, for the whole system security (voltage and frequency stability in addition to congestion management at transmission level), and DSOs for implementation of actions requested by TSOs commands or needed in order to solve local problems (e.g. local under/overvoltage, congestions).

Innovative solutions are presented hereinafter in this chapter. The aim is to highlight the most promising flexibility resources and their characteristics on the basis of the national developments.

4.1 List of innovative solutions

The Table 23 and the Table 24 list the possible innovative flexible resources respectively for LV-MV and HV-EHV levels in Belgium, Italy and Japan. The state of the art of these flexible resources is represented so as to understand which are the solutions with the main chance to be exploited.

The innovative flexibility solutions at distribution MV level are used for the requirements at distribution and transmission levels. In this report we further discuss about the latter.

Table 23: innovative flexibility resources at distribution MV level

Type	Sub type	Belgium	Italy	Japan
Demand Response	Industrial load	■■	■	■■■
	Household load	■	■	■
	Electric vehicles		■	■
PV output modification		n.a.	■■ ([17])	n.a.
Storage	Battery Li-ion	■	■	■■■■
	Battery Vanadium Redox		■	
	Battery NaS		■	■■■■
	Flywheel[28]			
	SMES[29]			
	Supercapacitor			
	Heat storage			■
Battery storage associated with PV[30] for fast frequency control supply			■	
Battery storage associated with wind generators for synthetic inertia supply			■	
Line Dynamic Thermal Rating[31]				

■ studied
■■ endorsed
■■■ planned/under construction
■■■■ commissioned

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[28] Flywheel works by accelerating a rotor to a high speed and maintaining the energy in the system as rotational energy.

[29] Superconducting Magnetic Energy Storage systems store energy in the magnetic field created by the flow of direct current in a superconducting coil.

[30] PV generation systems cannot provide inertial response unless innovative solutions are adopted: e.g. synthesizing an inertia emulator by means of utilization of battery energy storage systems (BESS) together with proper inverters aimed to simulate a traditional generator inertial response.

[31] Maximizing line capacities exploiting the temperature variability due to climatic conditions. By this way, a lower amount of network congestions is highlighted and, consequently, lower is the possible need of RES curtailment for congestion management.

Table 24: innovative flexibility resources at transmission HV level

Type	Sub type	Belgium	Italy	Japan
Demand Response	Industrial load		■	■
PV output modification		n.a.	■■ [27]	n.a.
Storage	Battery LI-ion		■	■■■■
	Battery Vanadium Redox		■	■■■■
	Battery NaS		■	■■■■
	Flywheel			■■■■
	SMES			
	Supercapacitor			
	Heat storage			■
	Seawater pumped storage	■		■■■■
	Conventional PHS	■		■■■■
Battery storage associated with PV for fast frequency control supply			■	■
Battery storage associated with wind generators for synthetic inertia supply			■	■
Synthetic inertia associated with wind		n.a.	n.a.	n.a.
Enhanced performant thermal power plants			■■	■
Line Dynamic Thermal Rating			■■	■
Cross-border balancing market			■	■■■
HVDC VSC links			■■■	
FACTS devices			■■■■	

■	studied
■■	endorsed
■■■	planned/under construction
■■■■	commissioned

Concerning demand response, this option is worldwide endorsed and participation of electric vehicles is in general considered a reasonable opportunity. Indeed, EVs may behave as a load, a supplier of electricity to the grid or an energy storage device and, by means of smart grid enabling technologies, utilities can manage EVs charging time and rates. At every voltage level, industrial/commercial can have the flexibility to adjust their energy consumption for production processes or air conditioning but also household, at low voltage level, can participate in DR thanks to smart grid technologies availability.

PV output modification is presently achieved by means of local logics, e.g. over-frequency droop or tripping based on local frequency signal. The innovative concept is based on adoption of remote signals/commands sent by TSO or by DSO on request of the TSO. Remote signals may be also sent automatically, in the future, by innovative special protection schemes based on identification of critical events (e.g. contingencies) or based on monitoring of selected system quantities and aimed to preserve operational security.

Despite the present high costs, battery energy storage BES for ancillary services is one of most promising kinds of flexible resources with high performances in terms of response speed; it is commonly considered a solution but, in general, at early stages on MV level

(Table 23). On HV level (Table 24) battery storage is already planned in Japan and some pilot projects are adopted in the main islands of Italy (Sicily and Sardinia).

Synthetic inertia[32] can be supplied by BES associated to wind while BES association with PV generation can be exploited for fast frequency control[33] provision. In case of converter-based WIND, synthetic inertial response can be gained by increasing or decreasing the turbine speed, without need of BES. Inertial response requirements have been already defined within the Grid Code of Hydro Quebec Transénergie (HQT) – Canada ([37];[38]): wind power plants with a rated output grater then 10 MW must be equipped with a frequency control system. The Irish Commission of Energy Regulation has published the technical definitions of the synthetic inertia to be considered as ancillary service ([37], [39]). The ENTSO-E Network Code on Requirements for generators allows system operators to require emulate inertial response from wind generators, depending on their size and geographical location ([40]). In Brazil, the Operador Nacional do Sistema Elétrico (ONS) is changing the grid code and already added, in the auctions rules, the requirement that all WPPs, connected at transmission HV level, need to provide reserve in case of events of under frequencies, using synthetic inertia ([37]).

Concerning the enhanced performant thermal power plants, in the context of AEEGSI[34] survey for the consultation n. 557/2013 ([30]), the Italian TSO "TERNA" implemented a study on flexibility resources. In this study, the main highlighted improvements are: 1) need of starting time (between TSO command and reaching of minimum generated power) lower than 2 hours in order to allow activation of tertiary reserve in real time; 2) a lower number of hours of continuous operation of thermal power plants in order to follow the new profile of net load by many daily cycles characterized by hours with very low values followed by hours with high values (4÷8 hours in operation and 4÷6 hours out of service); 3) fast ramp (about 50MW/min) in order to follow the fast upward load ramps in the evening when the high share of PV generation decrease; 4) need of a higher amount of enabled plants for dispatching services supply in order to get a higher amount of downward reserve since it seems to be not enough for perspective analysed scenarios. In conclusion, the ancillary services market should be organized in order to incentivize higher performances of plants enabled to supply these services.

4.2 Flexibility on the demand side obtained through demand response

The development of innovative demand response services can allow, for customers, the possibility to control their power exchange and to change their consumption patterns.

The basic purpose of Demand Response DR is to lower or shift consumption during periods of high wholesale market prices. Anyway, Demand Response DR is worldwide endorsed (see also Table 25) in order to be exploited for peak shaving, valley filling, power balancing and congestion management. Peak shaving and valley filling have the purpose of improving the grid accommodation capacity of power flows in case of highly variable net load. Figure 8 depicts the DR usefulness in case of net load (or residual load) affected by high PV penetration in the midday hours.

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[32] Proportional-derivative control of frequency (emulation of inertial response of synchronous machines).

[33] Proportional control of frequency.

[34] Italian Regulatory Authority for Electricity Gas and Water.

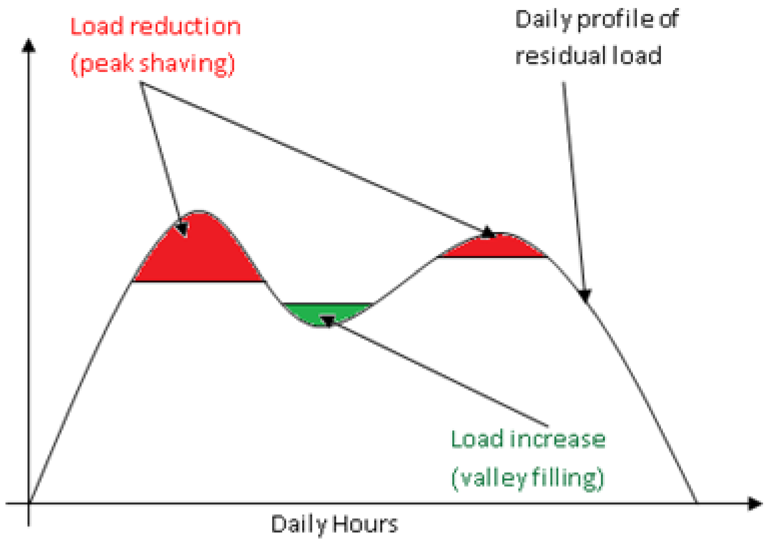

Figure 8: demand response application with variable residual (net) load

Power balancing by means of DR can face the on-going displacement of traditional regulating generation in the context of the increased variability of generation due to not-programmable renewable sources. Congestion management, also at transmission level, may be then supported by means of control of demand aimed to match power flows with grid transmission and distribution capacity.

Potential drivers of DR may be: the average retail price of electricity, a proper electricity market structure, the presence of a dedicated demand-side policy/regulation, the generation mix with high level of renewables penetration and reduced reserve margins.

In Belgium, DR is used in order to provide balancing services for TSO. Large consumers on transmission and distribution level are involved.

In Italy, DR is not yet used and the transmission grid code of the national TSO doesn't consider load units as possible sources for dispatching services. Indeed, at present, only disconnection of preselected loads from power system is implemented in order to maintain security of operation. A change in the next years is anyway expected; after all demand participation into ancillary and balancing services market has been yet approved by directive EU 2012/27 on energetic efficiency accepted by Italian legislative decree 102/2014. The Italian Regulatory Authority for Electricity Gas and Water AEEGSI, with deliberation n.111 of year 2006 (article 59.1), doesn't distinguish between generation and demand for the integration with the TSO control systems. Anyway the presently adopted requirement of 10 MW minimum rated power has to be modified with a lower value allowing the participation in MSD market of loads able to supply dispatching services.

Aggregation of demand, for DR, is in general deemed as a necessary option since it is not reasonable to integrate each participating small consumer into an ancillary services market. Aggregators aggregate a number of individual participating customers into a coherent group of business players and, then, combine DR capacity by entering into contract with the participating consumer. In some cases, the aggregators have bilateral agreements with the local distribution company LDC or an Energy Retailer to market and manage DR activities. In other cases, aggregators are able to aggregate DR capacity and offer it directly into the wholesale power market like any other generation resource.

Table 25: Status of demand response

	Belgium	Italy	Japan
Status of demand response "DR" for system security or reliability	Used	foreseen	Foreseen
Present or foreseen DR service providers	aggregator	aggregator	Foreseen providers: Local Distribution Company; Energy retailer; Aggregator
Present/expected DR procurement scheme	Bilateral agreements between DR provider and TSO/ISO	Market regulated and/or Bilateral agreements between DR provider and TSO/ISO	Bilateral agreements between DR provider and TSO/ISO
Adoption of communication infrastructure and meter data systems allowing auto-DR implementation	no	no	Not yet but it is foreseen
Kind of loads suitable for demand response	Industrial loads. Heat pumps (studied). Electric vehicles (studied)	Industrial loads domestic refrigerators water heaters air-conditioning electric vehicles	domestic refrigerators water heaters air-conditioning vending machines electric vehicles
Possible drivers for users engagement in DR implementation	I) industrial loads (bilateral contracts with payments); II) Household loads (pricing mechanism; currently not available); III) Electric vehicles (pricing mechanism; currently not available)		Pricing mechanism for industrial loads, household and electric vehicles Legislation rules for industrial loads

4.3 Flexibility by installations of storage with adoption of new technologies

Storage will play more and more a key role for power system operation in all the areas with high penetration of variable renewables and several technologies are already available for battery storage.

Battery storage

Battery storage can limit power pics and power dips due to fast meteorological changes by means the availability of very fast control. Besides energy storage, batteries can supply services like:

- forecast error compensation
- net-load levelling
- frequency control,
- peak shaving,
- voltage control,
- synthetic inertia.

At distribution level, batteries exploitation is commonly expected for load levelling, back-up for power supply and residential management. At transmission level some demonstrative centralized battery storage projects in Italy and Japan, have the aim to verify the technical-economic feasibility of ancillary services supplied by batteries, following commands directly operated by the system operator. As already mentioned in chapter 3, in Italy two significant projects are being carried out about centralized battery storage:

- 35 MW of "energy intensive" battery storage to improve the flexibility in managing renewable energy plants and to increase the hosting capacity of the grid in the southern continental area of Italy;
- 2x8MW of "power intensive" battery storage in the two major Italian islands (Sicily and Sardinia) aimed to increase the operation security in the power systems of the two areas.

In Japan, batteries are in commercial use or pilot stage in various use cases including:

- self-consumption at houses (Lithium-ion),
- load levelling (at major demands such as shopping centres),
- wind firm output levelling (Lithium-ion and NaS),
- transmission/distribution line voltage profile improvement under PV penetration (Lithium-ion),
- frequency regulation and net-load levelling (Lithium-ion, flow, NaS).

Pumped Hydroelectric Storage

In Belgium also PHS (Pumped Hydroelectric Storage) solution is studied (at early stage) at transmission level, while distributed batteries storage are seen as a possible solution only at distribution level.

In Japan, there is an amount of 25 GW pumped storage of conventional and adjustable-speed types, including sea water pumped storage of adjustable speed type.

4.3.1 Synthetic inertia and fast frequency response supply by battery storage

The inertia of the power systems is the physical "resistance" to frequency change. It is provided by rotating synchronous machines with heavy rotors. For example, in case of under-frequency, synchronous rotating machines convert kinetic energy into electrical power injected to the grid, providing an instantaneous support to angular stability of the system. Lower inertia means, for a given power unbalance, higher frequency deviations and higher rate of change of frequency "ROCOF" (index used in various protection devices/schemes like automatic load shedding). As shown in Table 26, PV introduces null inertia against the relevant inertia (3 to 10s) of thermal generators.

Table 26: typical inertia values for the different kind of generators

	H [s]
Hydro generators	2 to 5
Combined Cycle generators	5 to 10
Steam turbine generators	3 to 8
PV and full converter wind generators	0

With increased PV generation, its effects on system inertia have to be mandatorily taken into account, especially in the case of isolated power systems like the Japanese one or weakly interconnected networks like the one of the Sardinia island (Italy), asynchronously interconnected with the Italian peninsula i.e. without external contribution to inertia. An example is given by the dynamic[35] simulation shown in the Figure 9 were a 10% unbalance is considered in Sardinia (perspective scenario year 2020): the total rated power of the rotating machines is 2640 MW and the generation loss is the 10% (264 MW). Two different cases of system inertia are considered: $H = 4.14\ s$ (blue curve), like around the presents situation, and H=2.07 s (red curve), assuming a high penetration of PV and full-converter wind generation. It can be seen how, lower inertia involves larger frequency excursions and ROCOF; this simulated case is not critical[36] but shows how lower inertia can involve an increased probability of under frequency load shedding.

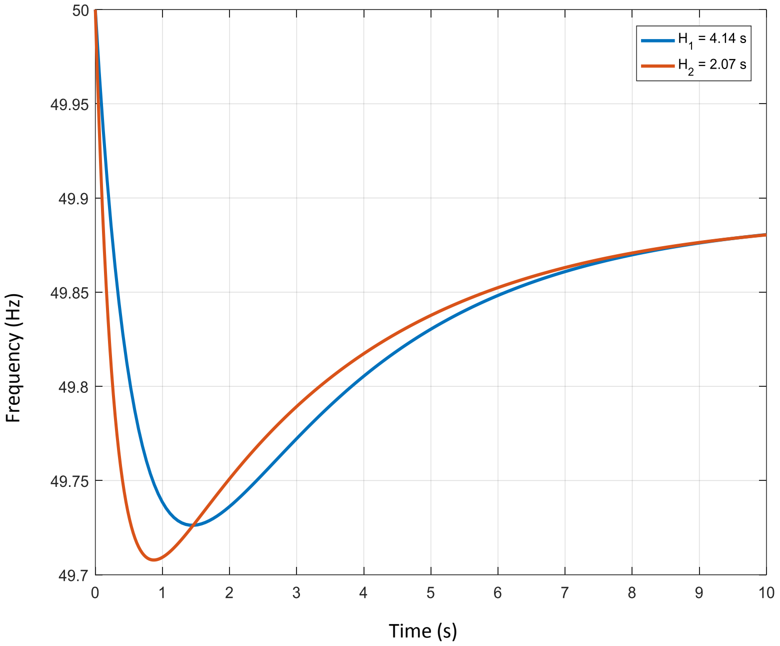

Figure 9: Dynamic simulation, with different values of inertia, of a big thermal generator loss in the Italian Sardinia Island (source: Ricerca sul Sistema Energetico - RSE S.p.A.)

In the recent years, scientific literature proved how batteries, associated with variable renewables, represent a promising solution for synthetic inertia supply that is expected deployed in tenths of seconds with proportion to the time derivative of the power system frequency.

Controller structures for Inertial Response are proposed by scientific literature([41], [42]), e.g. in case of battery storage embedded in wind power plants in order to increase their synthetic inertial response. It is worth reminding that, as already mentioned, converter-based WIND can supply synthetic inertial response by increasing or decreasing the turbine speed, without need of BES ([43], [44]). A derivative control method based on the rate of change of frequency (ROCOF) was proposed in literature in order to emulate

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[35] RMS (root mean square) simulation in the time domain.

[36] In Sardinia ±500mHz range around 50 Hz is allowed by the defense plan of the Italian electrical system. In Europe ±800mHz is allowed as frequency peak and 0.5÷1Hz/s is the present accepted ROCOF by ENTSO-E (2Hz/s in the future). Reference: *ENTSO-E Frequency Stability Evaluation Criteria for the Synchronous Zone of Continental Europe*.

the inertial response of a synchronous generator. The equation of motion of a rotating synchronous machine is given by:

$$2H\frac{df}{dt} = T_m - T_e$$

Where:

- H is the inertia constant (2...5s for hydro generator, 5...10s for combined cycle, 3...8s for conventional generator);
- $\omega = 2\pi f$ is the rotor angular speed;
- T_m is the mechanical torque;
- T_e is the electromagnetic torque.

Of course, the inertia constant is 0s for full converter wind and PV, so inertial control of such devices can enable them to emulate an inertial response with inertia constant H by changing active power reference by the quantity

$$\Delta P_{INERTIA} = -2H\frac{df}{dt}$$

A base scheme for inertial control (Figure 10), with grid frequency as input and active power reference as output to the actuator, may include:

i) a derivative block for rate of change of frequency "ROCOF" calculation with low-pass filter $\left(T_{filter} = 20ms\right)$ for noise treatment since derivative control is sensitive to the noise;

ii) a proper gain for active power reference $P_{OLD\ REFERENCE} + \Delta P_{INERTIA}$ calculation based on above equation (value similar to the inertia constant of a synchronous generator);

iii) a ROCOF dead-band ($\pm 0.05 Hz/s$) block aimed to limit control action to significantly fast frequency deviations.

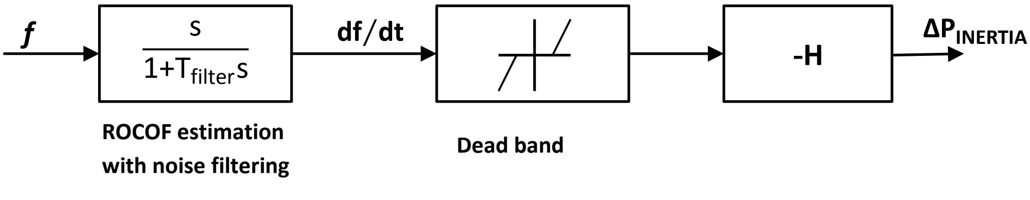

Figure 10: Block diagram of a derivative control aimed to inertial response - wind associated storage (picture based on [43])

Given a certain under-frequency event, the synthetic inertia allows to have a lower initial ROCOF [df/dt] and a higher time to reach the minimum frequency point.

It's worth noting that, although the above control can be in principle also valid for PV generation associated with storage, it's necessary to distinguish the different dynamic behaviour of rotating turbine wind and static PV. For example, the most common method to enable frequency response in converter-based wind is by increasing or decreasing the turbine speed; that practice cannot be applied to PV since no rotating parts are involved. PV may be associated to storage and also kept in de-loaded operation, i.e. with a certain power margin at a given solar irradiation, in order to supply itself a fast frequency response ([45], [46]). In other words, PV plants can be operated below their optimal operating point (Maximum Power Point Tracking) at reduced/increased DC voltage with respect to the optimal DC operation voltage (V_{MPPT}). The control, for fast frequency response, of PV with storage can be similar to the speed governor of conventional synchronous generators used for primary frequency control, i.e., a proportional controller based on system frequency deviation, avoiding the mentioned limitation of ROCOF due to noises. Given a certain under-frequency event, the fast frequency control allows to contain the minimum frequency value.

4.4 Communication infrastructure for demand-response and control of battery storage

Smart Grid is worldwide deemed as the base solution for managing the high penetration of variable RES. Smart Grid can be defined as "the convergence of information and operational technology applied to the electric grid, allowing sustainable options to customers and improved security, reliability and efficiency to utilities" [47]. Smart grids are therefore based on utilization of ICT communication infrastructures allowing observability and controllability of the grid, from distribution to transmission level.

Concerning centralized systems on HV transmission level (e.g. centralized large batteries on HV level or big industrial load used for DR), it is reasonable to assume the adoption of dedicated communication systems.

Concerning DR and the distributed batteries storage, standardized communication systems/protocols, such as IEC 61850 communication standard supply, in general, base concepts for realization of proper communication infrastructures. Accordingly with the Smart Grid needs, IEC 61850 is compliant with the following requirements:

- interoperability among typical elements of the grid, even if supplied by different manufacturers, by means of an open and proper communication tool;
- flexibility needed in case of possible power system evolutions and common language for information sharing;
- support of services aimed to real-time operation.

Main limits of IEC 61850 are: the complexity of proposed architecture; the high costs for the installation of servers and devices for data management; the limits due to adaptation to other existing protocols.

In Japan, Open Automated Demand Response (OpenADR) is the main candidate communication protocol while others are under discussion. The typical application of openADR concerns sending information and signals to cause consumers devices to be turned off during periods of high demand.

Based on the survey, Table 27 shows the possible communication infrastructures.

Table 27: Communication infrastructures for DR and distributed storage – existing/presumed

Belgium	Italy [48]	Japan
Wireless communication LPWAN	Internet Wi-Fi WiMAX Power Line Carrier	Internet Radio Power Line Carrier

Wireless communication will play a key role taking into account the larger and larger number of devices connected to the internet. Low-Power Wide-Area Network (LPWAN) can be an alternative solution to the internet; this kind of telecommunication network is designed to allow long range communications at a low bit rate (e.g. low number of bits that are conveyed per unit of time, among connected objects). Long range LoRa, standard of LPWAN, is deemed very promising (e.g. by Belgium). Each standard uses a different technique to maximize range while minimizing transmission power: LoRa radios use a modulation technique that can find signal well below the noise floor.

Wi-Fi and WiMAX are both wireless communication protocols based on radio waves utilization (wireless). Wi-Fi can typically cover areas from tens to hundreds of meters with a transfer data speed in the range 54÷125 Mbps[37]. WiMAX can cover distances of tens of kilometres with a speed around 75 Mbps.

The internet is the most widespread infrastructure. Anyway, this solution involves the need of ensure data and processes security and it may be affected by too much high response times for the application in real-time operation.

Power line carrier PLC communication in power systems is already adopted for telemetry (i.e. measurement from remote location) and remote control (e.g. for transmission line protections). In Italy, meters adopted by the main distribution utility ENEL are based on PLC communication with adoption of communication standard ISO 14908. The main advantage of PLC solution is the exploitation of the existing grid lines; anyway, with that solution, noises may significantly affect transferred information and, in case of line tripping or network switching, continuity of operation is not ensured.

4.5 Cross border balancing market

In operational planning, variable RES involve uncertainty around forecast and variability. Power balancing capability across national borders is a proper solution aimed to reduce the impact of the RES variations. It was already undertaken within continental Europe (see also ph. 2.1.2) and it is under discussion in Italy and in Japan, even if the latter is not presently interconnected. At present in Italy, with low load, the possible PV surplus can involve the reduction of thermal generation with consequent less regulating capacity. In general, when reserve is not sufficient, the Italian TSO changes the cross-borders exchange schedules.

Cross border balancing market seems to be a proper scheme to manage power balancing among countries. It's worth noting that development of cross-border interconnections with neighbouring countries allows higher exchange volumes ensuring, in first instance, higher market competitiveness but also the possibility of power reserve sharing among countries. At transmission level, the new VSC HVDC technology is a proper solution in

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[37] Megabits Per Second.

order to manage power transfer in the context of a cross border balancing market. E.g. between Italy and France, a new 1200 MW rated HVDC is under construction in order to increase transmission capacity between the two countries.

5 PV output management for system operation

As pointed out in Europe with the occurrence on the 25 March solar eclipse ([16]), controllability and observability of PV have to be endorsed in order to support utility operators in terms of planning and operation.

Concerning controllability of PV, as successfully occurred in Italy, it is possible to disconnect in advance a share of the installed PV production but, such practice on a large scale, need the knowledge of: i) the exact amount of PV feed-in to be switched off; ii) timing of PV switching off and switching on; iii) logical steps for PV switching on; iv) impact of shutdowns on the system.

Concerning observability of PV, a clear description of the installed PV capacity and their capabilities is needed for the accuracy of forecast studies (technical data, retrofitting campaign, disconnection/reconnection settings and logics, etc.)**.** Real time measurement of the dispersed PV generation may be then the key element for adapting, in real time, the strategy for operational security.

5.1 Curtailment of connected PV output

A considerable RES energy production may involve temporary critical situations in the system operation mainly because of over generation of RES which leads to the reduction of the regulating reserve and the reduction of global inertia, especially. As already mentioned, the inertia issue is critical in case of PV and “full converter” Wind generation. Consequently the grid may be exposed to greater vulnerability.

RES capability to provide ancillary services may be one of the affordable technical solutions and consequently a good driver toward high PV penetrations. Moreover, participation into markets for ancillary services may be an interesting option, for PV, to retrieve an additional income as discussed and studied with wind generation.

PV curtailment can be seen as a sort of ancillary service due mainly to grid congestions and system balance but also for voltage deviations and for system voltage-related stability.

The development of variable DG generation has involved new control problems since it is dispersed in thousands or millions of generators connected to distribution networks. Therefore special procedures are needed to take into account the nature of dispersed generation and the role of DSOs.

National practices, especially in countries with high PV penetration are useful to understand how manage the PV output in case of violation of operational grid boundaries.

5.1.1 Belgium

At present, no procedures are adopted, in Belgium, for PV power curtailment aimed to transmission level security, at MV and LV distribution levels.

No HV connected PV is present but, in principle, same rules, as other generation types, would be applied.

5.1.2 Germany

In Germany an active power reduction is foreseen in case of over frequency (>50.2Hz) by means of application of a local P(f) characteristic. A droop function is adopted as suggested in the technical conditions for the connection to the medium voltage network and low voltage network (e.g. see Figure 11).

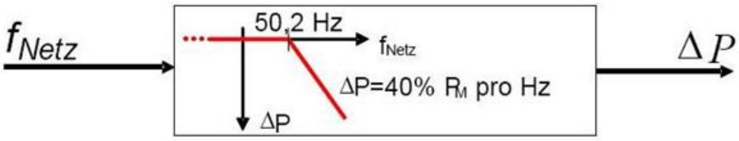

Figure 11: Droop function in case of over-frequency (Germany- [21])

Furthermore, congestion management is applied with the definition of requirements concerning active power curtailment for the HV, MV and LV levels.

Procedures for PV active power curtailment in Germany, aimed to transmission and distribution system operational security, are shown in Table 28. The procedure for active power curtailment can differ between the DSOs. At LV level, the active power curtailment is usually activated for a LV grid area (for example zip code area) e.g. via a radio ripple signal. At MV level, the minimum size of the interested PV units can differ per DSO, larger PV systems (e.g. PV systems with P_{rated} > 500kW) have a direct connection with the DSO network control centre for remote control and online power reading.

Table 28: procedures for PV active power curtailment at distribution level (Germany)

Voltage level	Size of interested PV units	Activation	Communication technology
LV (EEG 2014)	P_{rated}>30 kW remote interface	Usually manual for an LV area (e.g. zip code)	GSM[38], Radio Ripple Control
	P≤30 kW remote interface or fixed limitation of the active power to 70% on nominal power		
MV	Based on DSO	Remote-controlled by DSO	--

Reactive power control for voltage support is also required in the HV, MV, and LV levels, with different specifications per voltage level.

5.1.3 Greece

At present, no procedures are adopted, in Greece, for PV power curtailment aimed to transmission level security, at all the voltage levels.

5.1.4 Italy

In Italy, PV plants, on the basis of size and date of connection, contribute to operational security since they have to comply with the national grid code ([26], [27]).

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[38] Global System for Mobile Communication.

A curtailment is foreseen in case of frequency higher than 50,3 Hz, with 2.4% of permanent frequency droop[39] and total power cut at 51.3Hz (see Figure 12). That requirement (ref §4.1 AEEG 84/2012 [22]) is applied to:

- PV on LV level with $\mathrm{P_{rated}} \geq 1\mathrm{kA}$ and date of connection after 31/12/2012;
- PV on MV level with $\mathrm{P_{rated}} \geq 1\mathrm{kA}$ and date of connection after 01/07/2012;
- PV on HV level.

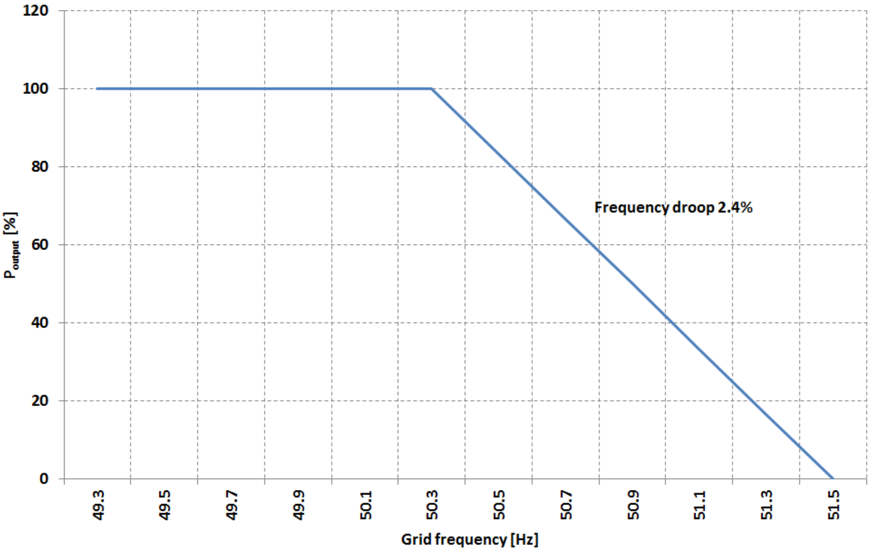

Figure 12: DG droop function in case of over-frequency (Italy; graphic based on [26])

PV systems on LV level

Remote signal for tripping is considered as input in the control schemes of the interface protection system of PVs having $P_{rated} \geq 1\mathrm{kW}$ and installed after July 1st 2012 [22].

PV systems on MV level

The Italian TSO TERNA adopts the "RIGEDI" procedure (year 2014 [17]) for DG curtailment in case of emergency operational conditions of the national electric system: the interested generators are PV and WIND connected on MV distribution level with rated power $P_{rated} \geq 100\mathrm{kW}$. Different shedding schemes, shown in Table 28, are foreseen by the RIGEDI procedure.

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[39] The frequency droop of a generator is equal to the quotient of the relative quasi-steady-state frequency error on the network and the relative variation in power output from the generator associated with the action of a frequency containment controller (e.g. primary controller on the basis of ENTSO-E glossary): it can be expressed as:

$$100 \cdot \left(\frac{\Delta f}{f_{NOMINAL}}\right) / \left(\frac{\Delta P}{P_{NOMINAL}}\right).$$

Table 29: RIGEDI schemes for DG active power curtailment at MV level (Italy; [17])

Procedure scheme	Voltage level	Size of interested PV units	Activation	Communication technology
GDPRO	**MV**	$P_{rated} \geq 100$ **kW**	Manual with forewarning	--
GDTEL			Remote-controlled by DSO	GSM/GPRS or satellite channel
GDRM			Remote-controlled with TSO command via DSO	TSO↔DSO: Dedicated channel TSO↔DSO: GSM/GPRS or satellite channel

The GDPRO scheme is implemented on DG connected to the grid by means of not dedicated lines whit presence of consumption units. Generation shedding is performed by plant owner on request by distributor.

The GDTEL scheme is implemented on DG feeding-in all net[40] production on the grid and connected via dedicated line that can be opened by motorized switch-disconnector on the basis of remote triggering by the DSO in case of request by the TSO.

The GDRM scheme is directly applied by the TSO defence system via the communication with the remote control system of the DSO.

In general, the RIGEDI procedure, waiting for the full implementation of the smart grids, takes into account that:

- the GDPRO plants are not remote-controlled and not overseen therefore a congruous forewarning is needed for shedding;
- only some plants are remote-controlled for remote shedding in short time;
- some plants are compliant with GDRM procedure.

Since DG doesn't participate into the national market for ancillary services (MSD), no economic merit order is considered in the generation shedding; this last is implemented only on the basis of a uniform distribution in compliance with operational security of the national transmission system.

In case of RIGEDI-GDRM a dedicated communication network should be implemented between TSO and DSO. Already existing channels for remote control are allowed with the condition of separation between present data exchange (e.g. data metering) and RIGEDI communication/commands. On the TSO TERNA side, the connection has to be protected by a firewall. A new connection has to be agreed by the DSO and the TSO with consequent communication of the IP internet protocol access by the TSO to the DSO. The GDRM plant should then be linked to DSO by means of GSM/GPRS modem connected via a communication network. DSO is synchronized by means of GPS or by means of a satellite channel where GSM/GPRS service is not covered.

PV systems on HV level

Besides in case of unacceptable over-frequency, the TSO can ask to PV generators on HV level to curtail their power output in case of: grid congestions, risk of overloading, risk of instability, steady state unacceptable over-frequency ([27]). The power limitation has to be implemented by PV plant owner, via remote control, within 15 minutes after TSO communication. In case of agreement between PV owner and TSO (not mandatory), a remote control can be implemented in order to allow the direct remote limitation

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[40] Taking into account absorption of the plant auxiliary services.

command by the TSO. Power limitation steps have to be, at least, 10% of the installed capacity.

5.1.5 Switzerland

Mostly, no procedures are adopted for PV power curtailment aimed to transmission level security, at MV level. Power curtailment application is up each individual DSO.

No HV connected PV are present.

5.1.6 Japan

In Japan, before the rapid PV penetration under Feed-in-Tariff which was launched in 2012 just after the East Japan Great Earthquake, limited visibility and manageability were required with the PV systems.

Concerning the curtailment of medium sized PVs, with P_rated≥50kW and distributed on MV level, the manual interruption with forewarning is required. No need of dedicated lines for PV connection is foreseen. The adopted communication system is manual by phone.

Concerning the curtailment of medium sized PVs, with P_rated≥2MW and distributed on MV level, manual control by plant operator after TSO/ISO communication is required. Also in this case, the adopted communication system is manual by phone.

In January 2015, the enforcement regulation of the Act on Special Measures concerning the Procurement of Renewable Energy was revised, and PV system function of output control is required to maintain the security of bulk power system ([49]). This control function is obliged to all type of PV system interconnected LV, MV, or HV network.

In 2015, a national R&D project started to actually establish the technology to realize visibility and controllability of PV systems from roof-top scale to MW scale including additional DR measure combined with the curtailment signal.

In 2016, the Partial Revision of the Act on Special Measures Concerning Procurement of Electricity from Renewable Energy Sources by Electricity Utilities was approved and established by the Diet in May, and promulgated in June.

The Revised Act stipulates the revision of the new Feed-in Tariff (FIT) scheme to achieve both the introduction of renewable energy to the maximum extent possible and the curbing of the public burden ([50]). The major revisions are: 1) Creation of a new authorization system; 2) Revised method of setting purchase prices; 3) Revision of businesses obliged to purchase renewable energy and other regulations; 4) Revision of the arrangement for reducing surcharges on electricity rates.

5.2 Further flexibility from PV output modification

5.2.1 International trend

Flexibility of operation is the ability of a power system to adapt to changing balance between supply and load at any time scale. Flexibility is system specific, and is inherently tied to the physical characteristics of a system, its planning process and operational practices, market mechanisms and regulatory environment. Without sufficient flexibility, the system operators may need to frequently curtail the wind and solar generation thus reducing the capacity factors and revenue streams of the plants and causing negative prices, which in turn reduces the attractiveness of investments in new generation (both conventional and renewable). There is no universally accepted method for measuring the system flexibility. The analytic field for measuring flexibility is still evolving based on advances in resource and load modelling and forecasting, and stochastic analyses for understanding system operations over a wide range of conditions.

As discussed in Chapter 4, under the penetration of renewable generation with variability and uncertainty, a power system requires more flexibility from various resources including RES with variability and uncertainty such as PV and wind. Under the circumstance of reduced value of energy and increased value of flexibility, the value of RES will be increased when it supply not only energy but also flexibility to reduce cost of power usage and enhancing security of power supply.

The aggressive supply of flexibility is pursued earlier with wind generation which penetrated into many power systems earlier than PV. A modern wind generator or wind farm can supply ancillary services by means of various control functions including maximum power production control, power ramp rate control, delta control, synthetic inertia control, power system damping control. With those controls, there are several practices and many studies to utilize the functions in a power system.

In Europe, REserviceS Project (2012-2014; [51]) studied flexibility needs of a power system, technology candidate, economic analysis, market design and next R&D. In Denmark, for example, EaseWind (2011-2014; [52]) of ForskEL project studied the contribution of wind generation to various aspects including frequency regulation, synchronization, and dynamic stability. In Europe, there are diversified activities ([53], [54]) about technologies, regulation and institution aimed to realize the flexibility from PV and wind generation.

In the United States, under an initiative of the Grid Tech Team, research institutes such as NREL[41], ANL[42], LBNL[43] and EPRI[44], utilities, grid operators have been studying the controllability of PV and wind generation, their values and grid operation and institutions to realize the value. NREL, as an example, recently published a report on capacity reserves and frequency stability services from variable generation ([55]).

Provision of flexibility necessarily means a reduction of energy production of RES (e.g. for upward power reserve provision). Accordingly, in order to realize the utilization of flexibility of RES, it is inevitable to establish a regulatory framework and market mechanism.

5.2.2 Demonstration Projects

In this section, among many efforts of R&D of PV output modification, some examples of demonstration projects are described.

(1) US

The National Renewable Energy Laboratory (NREL) has a research area of "Active Power Control" where wind power control technologies were developed from 2013 to 2016. In 2014 report, [56] , NREL had summarized its research in the areas of active power control

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[41] National Renewable Energy Laboratory. Web address: http://www.nrel.gov/.

[42] Argonne National Laboratory. Web address: http://www.anl.gov/.

[43] Lawrence Berkeley National Laboratory. Web address: https://www.lbl.gov/about/.

[44] Electric Power Research Institute. Web address: http://www.epri.com/Pages/Default.aspx.

(APC) by wind power. The report focused on economics and steady-state impacts of APC by wind in the power systems, dynamic stability and reliability impacts, and controls design and testing activities. In one recent paper, [57] NREL has evaluated the impact of the wind generation provision of APC strategies on the U.S. Western Interconnection at various levels of wind power penetration (up to 80% instantaneous penetration).

In 2014-2015, t NREL, AES, the Puerto Rico Electric Power Authority (PREPA), First Solar, and the Electric Reliability Council of Texas carried out a demonstration project on two utility-scale photovoltaic (PV) plants to test the viability of providing important ancillary services from these facilities.

Fiscal year 2014 activities focused primarily on finding collaborative industry partners and planning activities for FY15 testing. First, NREL contacted various industry members to identify potential utility or independent operators as collaborators to demonstrate a PV power plant as an asset to the grid based on the selection criteria above. As a result, two PV power plant owners/operators agreed to become partners with NREL to perform such testing:

1. Ilumina PV power plant owned and operated by AES Corporation. This20-MW plant is located near Guayama on Puerto Rico’s south coast.
2. Pecos Barilla PV power plant owned and operated by First Solar Electric, LLC. This 22MW plant is located near Fort Stockton in Pecos County in West Texas.

General conclusions of the demonstration tests include the following:

- System-level modelling exercises will be needed to determine the exact parameters of each control feature to maximize the reliability benefits to PREPA[45] and ERCOT[46].

- All hardware components enabling PV power plants to provide a full suite of grid-friendly controls are already in existence in many utility-scale PV plants. It is mainly a matter of implementing controls and/or communications upgrades to fully enable these. Issues to be addressed in the process include communications protocol compatibility and proper scaling for set point signals. Although these are not significant barriers, dialogue and interaction between the plant operators and the system operators is an important component of implementation of advanced process control capabilities. Modifying programming logic may be necessary at multiple places in the chain of communications.

- Fine-tuning of the PPC[47] to achieve rapid and precise response is an important step and is non-trivial. It may be easier with newer equipment because of the faster response times of newer inverters and controller systems.

- FFR response by a PV plant requires precise tuning of PI[48] controllers for fast response times and avoiding unintentional oscillation of the output active power.

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[45] Puerto Rico Electric Power Authority.

[46] Electric Reliability Council of Texas.

[47] Portable program carrier.

[48] Proportional-integral.

- For optimum FFR performance, the exact amount of generation loss must be dispatched to participating PV plants as an active power set point, so the pre-fault frequency can be quickly recovered. This will require a low-delay communication infrastructure to deliver information on the exact generation loss to the utility control center with consecutive distribution of proper active power set points to all participating PV plants that provide FFR.

- Many utility-scale PV power plants are already capable of receiving curtailment signals from grid operators; each plant is different, but it is expected that the transition to AGC[49] operation mode will be relatively simply with modifications made only to a PPC and interface software (Figure 13).

- Fast response by PV inverters makes it possible to develop other advanced controls, such as power oscillation damping.

- PV power plants without energy storage are capable of providing many services to the grid, but market mechanisms and/or new interconnection requirements are needed to incentivize curtailed operation for any up-regulation service.

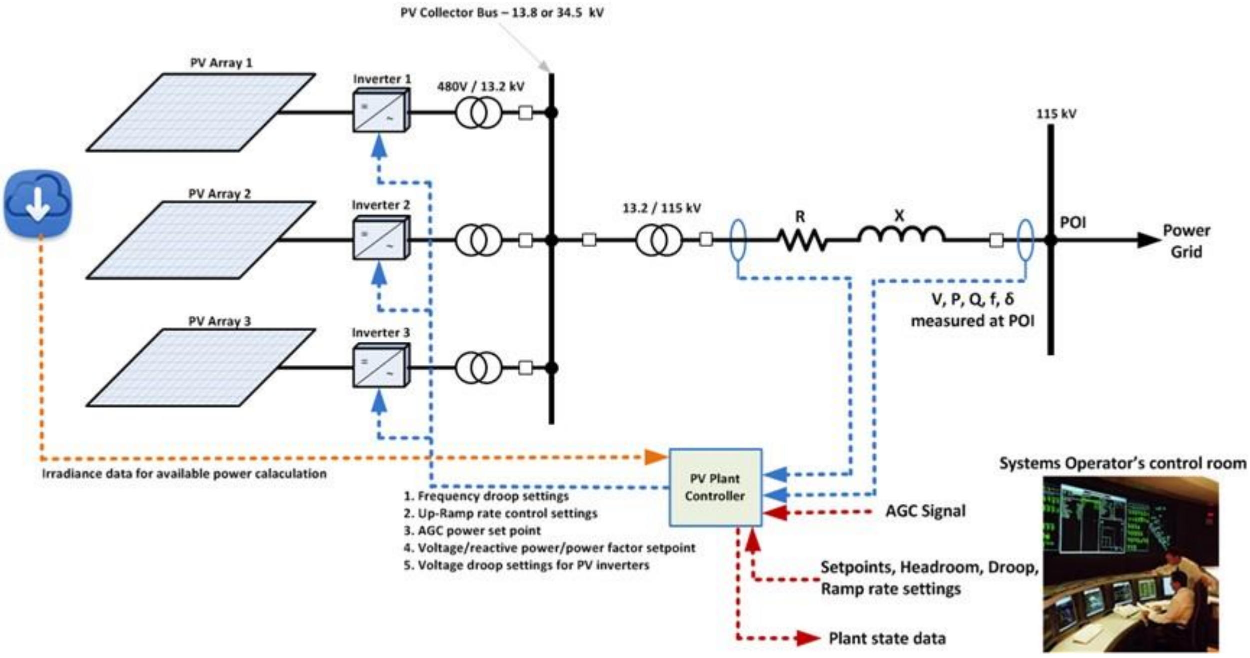

Figure 13: Grid-friendly PV power plant (source V. Gevorgian, NREL)

In 2016, NREL, CAISO and First Solar conducted demonstration testing of essential reliability services by a 300 MW PV power plant located in CAISO service area. This project demonstrated that advanced power electronics and solar generation can be controlled to contribute to system-wide reliability. It was shown that the First Solar plant can provide essential reliability services related to different forms of active and reactive power controls, including plant participation in AGC, primary frequency control, ramp rate control, and voltage regulation. For AGC participation in particular, by comparing the PV plant testing results to the typical performance of individual conventional technologies, it was shown that regulation accuracy by the PV plant is 24–30 points better than fast gas turbine technologies.

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[49] Automatic Generation Control.

The plant's ability to provide volt-ampere reactive control during periods of extremely low power generation was demonstrated as well.

The project team developed a pioneering demonstration concept and test plan to show how various types of active and reactive power controls can leverage PV generation's value from being a simple variable energy resource to a resource that provides a wide range of ancillary services. With this project's approach to a holistic demonstration on an actual, large, utility-scale, operational PV power plant and dissemination of the obtained results, the team sought to close some gaps in perspectives that exist among various stakeholders in California and nationwide by providing real test data.

(2) Japan

Japan has been experiencing rapid PV deployment since feed-in-tariff program was launched in July, 2012 one year after the Great East Japan Earthquake and Tsunami. Under the situation of rapid PV deployment, the Japan Government established "Working Group on Grid Connection of Renewable Energy (the Working Group)" in 2014 and a committee in 2015, to discuss about the carrying capacity in a balancing area and its enhancement, and to discuss about the improvement of the FIT program respectively. In the meantime, the PV penetration is affecting the stable operation of a power system in each of the balancing area in Japan according to the level of the penetration. Under the situation, several RE integration demonstration projects have been continually conducted Japan [58].

Figure 14 depicts a total schedule of the METI[50] demonstration projects related to renewable energy integration. In the Project No. 2 demonstrated an innovative inverter technology, demand response utilizing automated HEMS and a battery, and demand and supply planning and real-time operation simulation technology [59]. The project No. 3 demonstrated a two-way communication technology for the visibility and controllability of a residential-scale PV. Project No. 4 demonstrated the state-of-the-art PV generation forecast technologies with the review of utilities of system operation viewpoints.

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[50] Ministry of Economy, Trade and Industry .

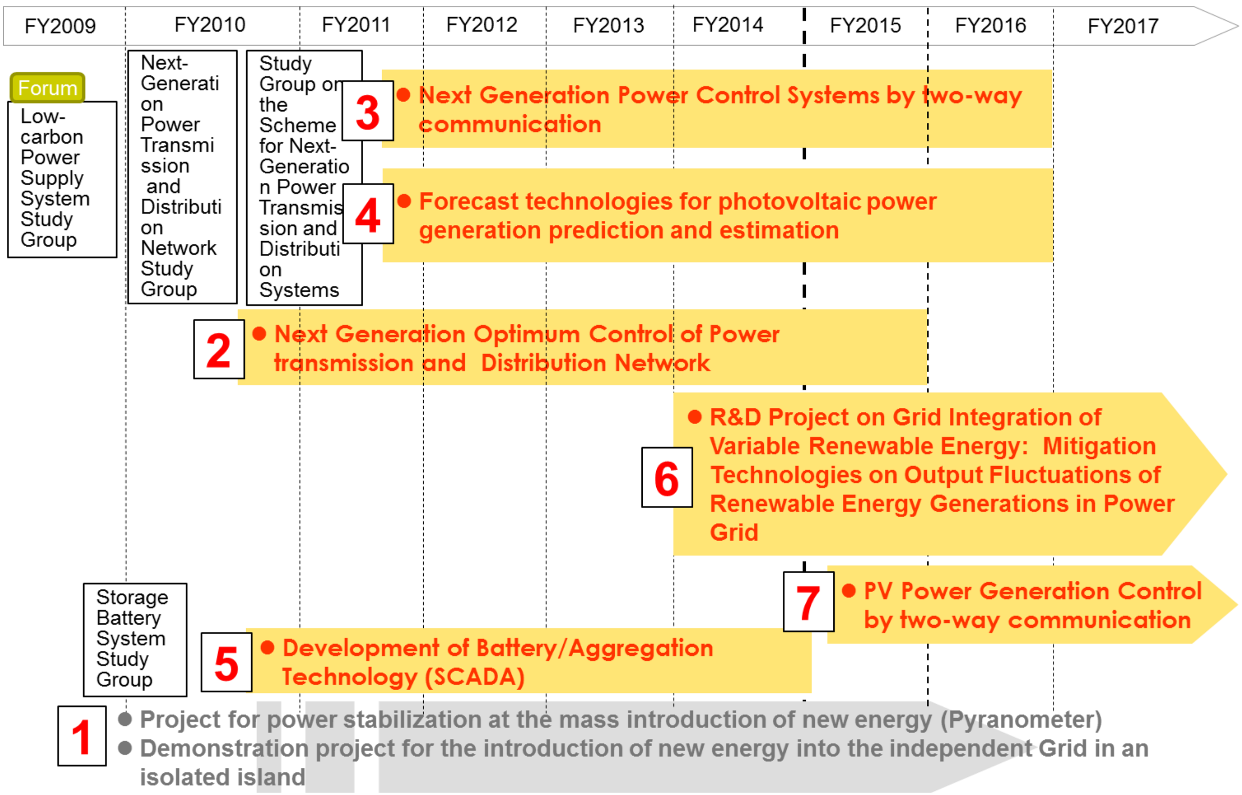

Figure 14: Progress of METI Demonstration Projects (Source: TEPCO)

From 2014, the national project package "Grid integration of VRE mitigation technologies on Output Fluctuations of Renewable Energy Generations in Power Grid" began with a project period of five years. The project includes themes of wind ramp forecast with actual wind farm monitoring, energy storage utilization, demand and supply planning and analysis, and integrated demonstration in an island (project No. 6 in Figure 14).

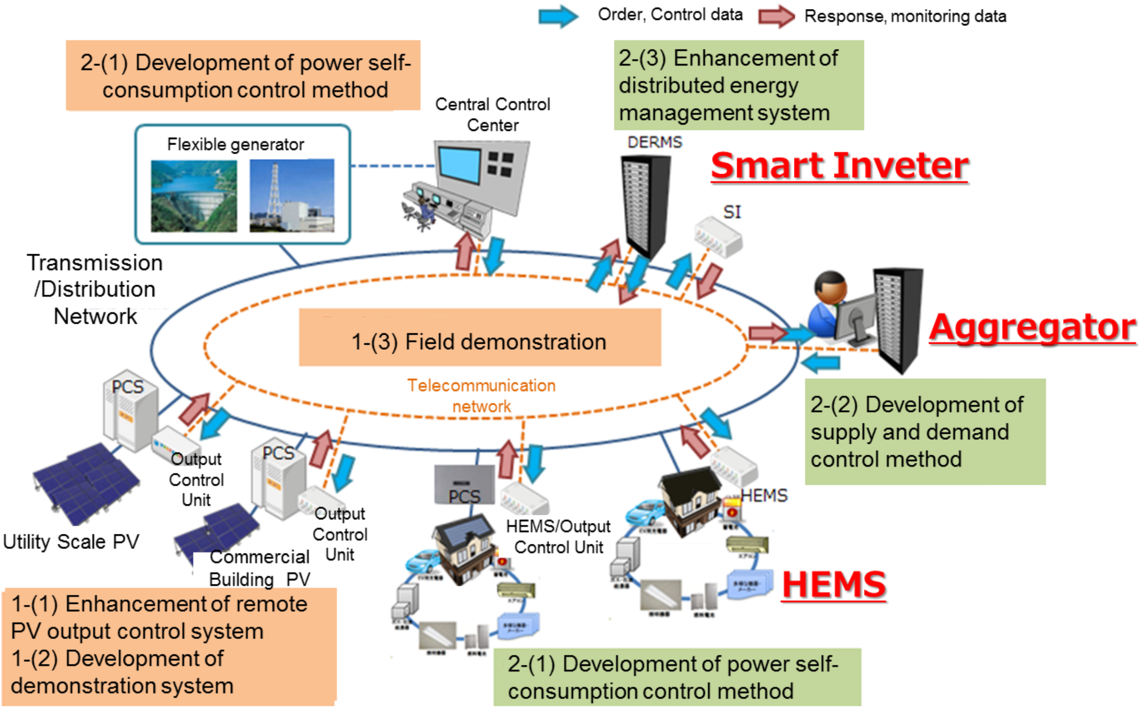

Figure 15: Project structure of National Project on output curtailment for PVs (Source: Project Material)

From FY2016, after the preceding study in FY2014, the same national project package added a new project with a schedule from FY 2016 to FY 2018, focusing on the PV output control and enhancement of PV output control method. The project is intended to establish the technology along with the rapid PV deployment under the feed-in-tariff program in Japan. The project includes the following development items as depicted in Figure 15:

R&D Item 1: Establishment of PV output control method for curtailment

Enhancement of remote PV output control system

Development of demonstration system

Field demonstration

Development of calculation technologies for optimal output controlled capacities

R&D Item 2: Enhancement of PV output control method

Development of power self-consumption control method

Development of supply and demand control method

Enhancement of distributed energy management system

5.3 Communication infrastructure for distributed PV output modification

Dispersed PV plants management involves the need of smart grids based on ICT infrastructures allowing plant observability and controllability from distribution and transmission levels.

Suggested communication infrastructures for PV remote control, such as demand response (§ 4.4), span over a wide range of solutions like those summarized in Table 30, based on the survey.

Table 30: Communication technologies for generation modification of distributed small-scale PV existing/presumed solutions

Belgium	Germany	Italy	Switzerland	Japan
Internet GPRS	for example GSM, radio ripple control, Internet, PLC	Power Line Carrier Internet Wi-Fi WiMAX	Normally no communication. Rarely one of the following: ripple control system (modulated on grid voltage); smart metering system (often optical fibre) to the substation; PLC to the home	Dedicated line Internet Radio PLC

Through promising intelligent control methods and remote control solutions the existing power grid infrastructure can be exploited allowing a higher penetration of distributed PV. Interoperability and standardized communication systems/protocols, such as IEC 61850 communication standard, are important keys to realize such intelligent approaches. Despite its inherent architecture complexity, as already mentioned IEC 61850 ensures: i) interoperability among elements, even if supplied by different manufactures; ii) flexibility in case of possible technology evolutions and common language for information sharing; iii) support of services aimed to real time operation.

In Japan, OpenADR is the main candidate communication protocol. It is typically used to send information and signals to consumers for switching off devices in case of high power demand.

Wireless communication is particularly suitable for PV output management, taking into account huge number of dispersed PV plants.

The internet infrastructure solution involves the need of ensure data and processes security and it may be affected by too much variable and high response times for the application in real time.

6 Conclusions

High penetration of PV generation, together with wind, creates specific challenges in terms of transmission system operation, introducing variability, uncertainty, null inertia with consequent higher needs and complexity in flexibility resources provision. This is due to both the increased requirements in ancillary services associated to power flexibility and to the displacement of conventional generation resources, i.e. the major traditional resources of flexibility for power system operation.

This report presented a review of existing and expected resources for flexibility in terms of: solutions for balancing (e.g. PV output management), PV forecast error compensation, peak shaving, inertia supply, congestions management.

The review was based on a survey involving national experts of 6 countries, namely Belgium, Germany, Greece, Italy, Japan and Switzerland With the aim to highlight items and scenarios of interest for PV integration studies.

Technical issues and flexibility

Solar PV in the electric grid is steadily rising in various areas worldwide. A significant PV installed capacity is expected in Japan, 64 GW by 2030 against 23.3 GW installed in 2014, and in U.S.A. with 100 GW by 2021 against 18.3 GW installed in 2014. High market share increases are expected in countries with low present capacity like Belgium, Greece and Switzerland and a certain growth is foreseen in countries like Italy and Germany, despite their already large PV installed capacity amount.

PV forecast is used for system operation planning in almost all participating countries. It is not used in Greece despite the not negligible installed capacity of 2.6 GW (against a maximum load around 9.2 GW). PV output has very fast and large variations with variable meteorological conditions. Therefore, highest reliability in PV forecast, such as for other variable RES, can only be achieved in the short-term. Flexibility resources must then be involved, aimed to compensate for the power imbalances caused by PV fluctuations or deviations with respect to the forecast. However a certain minimum time interval is needed for their activation; resources like battery energy storage systems are very fast, while thermal power plants are very slow. Consequently, the time horizon for operational planning is affected by the type of available flexibility resources and it cannot be lower than the minimum required time interval for resources activation.

Probabilistic approaches for the assessment of balancing reserve requirements, aimed to compensate RES forecast uncertainty, allow, unlike the deterministic methodologies, to contain over-estimation of the power reserve. In fact probabilistic approaches lead, accepting a certain risk, to the reduction of the reserve margins for operational security, in comparison with deterministic approaches aimed to cover the, possible but unlikely, maximum unbalance. A large amount of RES generation requires therefore probabilistic approaches for the assessment of the needed balancing reserve.

A possible concern consists in the changes in daily profile of net load, e.g. gross load minus distributed generation (DG) output. High PV penetration leads to lower net load in central day light hours with consequent risk of over generation since a minimum amount of traditional generation is currently considered to be required for operational security. Moreover, in the evening, the decreasing PV output leads to high upward ramps of net load with risk of slow system response to load ramp. Keeping in mind the above issues, it is necessary to endorse new highly performant flexibility resources, which can be quickly available if needed, such as: i) enhanced performant thermal power plants allowing short starting time, lower number of hours of continuous operation, fast ramp; ii) DG output modification; iii) demand response (DR); iv) battery storage.

The basic purpose of DR is to lower and/or shift consumption during periods of high wholesale market prices. Anyway, DR is, in general, endorsed in order to be exploited for peak shaving, power balancing and congestion management. Participation of electric vehicles in DR is then considered a reasonable opportunity.

Despite the present high costs, battery energy storage BES for ancillary services can be one of most promising kinds of flexible resources with high performances in terms of response speed. Battery storage can limit power pics and power dips due to fast meteorological changes by means the availability of very fast control.

DR and DG output modification involve the need of smart grids based on ICT infrastructures allowing observability and controllability of the grid, also at distribution level. ICT is needed to help system operation performed by TSOs, for the whole system security (voltage and frequency stability in addition to congestion management at transmission level), and DSOs for implementation of actions requested by TSOs commands or needed in order to solve local problems (e.g. local under/overvoltage, congestions). Standardized communication systems/protocols, such as IEC 61850 communication standard supply, in general, base concepts for realization of proper communication infrastructures. In Japan, Open Automated Demand Response (OpenADR) is the main candidate communication protocol. Wireless communication will play a key role taking into account the larger and larger number of devices connected to the internet. This last is the most widespread infrastructure. Anyway, this solution involves the need of ensure data and processes security and it may be affected by too much high response times for the application in real-time operation. Low-Power Wide-Area Network (LPWAN) can be an alternative solution to the internet. Power line carrier PLC communication in power systems is already adopted for telemetry and remote control. The main advantage of PLC solution is the exploitation of the existing grid lines; anyway, with that solution, noises may significantly affect transferred information and, in case of line tripping or network switching, continuity of operation is not ensured.

The progressive decommissioning of traditional generation, besides lower operating power reserve, involves system inertia reduction with lower inertial response in case of frequency perturbations. In the recent years, scientific literature ([24]..[27]) proved how batteries, associated with variable renewables, represent a promising solution for synthetic inertia supply that is expected deployed in tenths of seconds with proportion to the time derivative of the power system frequency. Moreover converter-based WIND can supply synthetic inertial response by increasing or decreasing the turbine speed, without need of BES. Controller structures for Inertial Response are proposed by scientific literature ([24], [25]), mainly in case of battery storage associated with wind. Proper controls for fast frequency control of PV were already presented but in-depth studies about that issue are still needed. This report has collected information about flexibility resources and explained them. Future reports are expected to give the analysis of the integration studies including the flexibility resources.

7 Recommendations

Operational flexibility and enhancement

Keeping in mind the minimum time interval for the activation of flexibility resources, the operational planning and the eventual ancillary services market should be, as much as possible, close to real time in order to get higher forecast reliability.

A large amount of RES generation requires probabilistic approaches for the assessment of the needed balancing reserve, avoiding over-estimations.

Cross border balancing has to be endorsed in order to reduce the impact of RES variations, sharing them within a larger power system instead of the single national ones.

Flexibility resources

New highly performant flexibility resources, which can be quickly available if needed, such as demand response DR, are even more needed in order to compensate changes in daily profile of net load due to high PV penetration.

A proper ancillary services market should be organized in order to incentivize higher performances of plants enabled to supply these services.

Potential drivers of DR, beside a proper electricity market structure, may be: the average retail price of electricity, the presence of a dedicated demand-side policy/regulation, the generation mix with high level of renewables penetration and reduced reserve margins.

Demand Response, in addition to DG output management, involves the need of smart grids based on ICT infrastructures. Many ICT solutions are or will be available in the next future, therefore accurate studies need to be performed in order to highlight the advantages and the drawbacks of each option (wireless communication internet; Low-Power Wide-Area Networks; Power line Carriers; etc.).

Proper controls for fast frequency control of PV are already presented in scientific literature but more in-depth studies about that issue are still needed in order to find solution for lower system inertia due to traditional generation decommissioning.

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