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QUANTIFICATION, CHALLENGES AND OUTLOOK OF PV INTEGRATION IN THE POWER SYSTEM: A REVIEW BY THE EUROPEAN PV TECHNOLOGY PLATFORM

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ABSTRACT: Integration in the power system has become a limiting factor to the further development of photovoltaics. Proper quantification is needed to evaluate both issues and solutions; the share of annual electricity demand is widely used but we found that some of the metrics which are related to power rather than energy better reflect the impact on networks. Barriers to wider deployment of PV into power grids can be split between local technical issues (voltage levels, harmonics distortion, reverse power flows and transformer loading) and system-wide issues (intermittency, reduction of system resilience). Many of the technical solutions to these issues rely on the inverters as actuators (e.g., for control of active and reactive power) or as interfaces (e.g., for local storage). This role requires further technical standardisation and needs to be taken into account in the planning of power networks. Forecasting, storage, and combination with other renewable sources are interdependent solutions to solve the intermittency issue. Finally, we found that PV is also an opportunity to reduce some investment required to upgrade existing power networks. Through integration with micro-grids and hybrid generators, it can form the basis of novel power systems.

Keywords: Grid Integration, System, Inverter, Storage

1 INTRODUCTION

Photovoltaic (PV) power generation has moved in just a decade from a curiosity to a significant part of power systems around the world. Solar PV is estimated to have provided 1% of the global electricity demand in 2014 [1]. The central point in levelised cost of electricity (LCOE) at the beginning of 2014 was about US$ 150 per MWh; there is now a significant overlap between the LCOE ranges of PV electricity and conventional power generation (natural gas combined-cycle turbines, coal, nuclear) [2], which means that solar PV can be cost-competitive at the point of generation in some regions.

As PV is essentially a distributed energy resource, it clashes with the centralised architecture of existing grids. Together with other renewable energy sources, it challenges the business models of incumbents in the power sector, be they network operators or power generators. Some of these incumbents may be tempted to exaggerate the negative impact of PV, and minimise its benefits. Others have already taken radical steps to adapt to this new situation [3].

The European PV Technology Platform aims at enabling the massive deployment of photovoltaics into the power system. It acknowledges the technical challenges that come with it. We believe that these challenges are best addressed through rational assessment of the situation and co-operation between the power and PV industries.

With this paper we set to clarify the terms of this discussion: how is penetration of PV into power grids best evaluated? What are the current levels? Which barriers may prevent increasing these levels? Which concepts have been put forward to open these barriers? Which benefits can PV systems provide for existing and new grids? We are confident that further collaboration with the power sector will lead to more robust knowledge and to a power system with PV at its heart.

2 QUANTIFYING PV PENETRATION: METRICS AND CURRENT LEVELS

2.1 Fraction of electric energy demand

The net fraction of electric energy demand met by PV generation can be defined at any scale, from a single building to the entire world. The integration period is generally one year. This metric is widely used in discussions of energy policy, although in that case PV is often combined with other "new" renewables such as wind.

Current values are (net basis, over one year) [4]:

- At EU level: about 3%
- At national level: from about 0.5% (The Netherlands) to 7.5% (Italy)

Depending on climate, energy mix, or patterns of electricity usage grid-related challenges in achieving similar fractions of electricity demand covered by PV may greatly vary.

2.2 Fraction of generation capacity

The fraction of generation capacity i.e., ratio between nominal PV (AC) power capacity and total installed generation capacity, is mostly used in market-related studies at national or continental scale. Indeed, it is a good indicator of the development of the PV market in terms of investments. It also characterises the challenges facing balancing authorities e.g., to guarantee that flexible capacity is available to compensate fluctuations in generation [5]. At the end of 2012, values of penetration as fraction of generation capacity were [6]:

- At EU level: 7.2%

- At national level: 13.2% (Italy), 18.4% (Germany)

However, to better reflect the situation of the power system, we would recommend using an availability-weighted share of generation capacity.

2.3 Installed capacity as a fraction of load

PV installed capacity (or maximum production) can be expressed as a fraction of minimum or maximum load [4]. This fraction can meaningfully be calculated at any level of the electricity network. At low and medium voltage levels, it characterises the need for grid reinforcement. At transmission system level, it qualitatively characterises the challenges in meeting base load demand while managing variability.

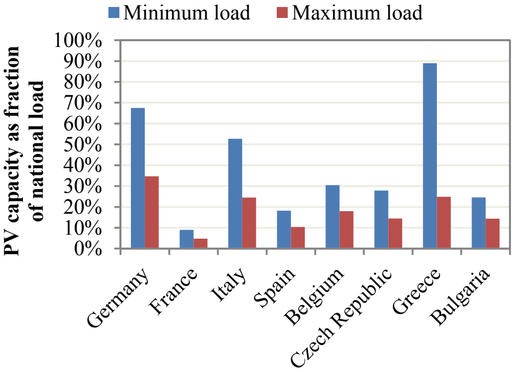

Figure 1: Installed PV capacity as of 2013 in eight European countries as a fraction of minimum and maximum load levels (mid-day peak between May and September) adapted from data in [4].

Thanks to the dispersion of PV systems in location and design, different PV systems produce at full capacity at different times. The ratio between the actual peak PV production and the load (instantaneous penetration level) is therefore lower than the figures shown on Figure 1. Instantaneous penetration levels have reached 77% in Greece and 46% in Germany. Several other countries have recorded maximum instantaneous penetration levels between 20% and 25%.

2.4 Penetration level of distributed energy resources

When considering distribution networks, especially at the low-voltage level, a penetration level can be defined as the ratio between the total AC peak power of installed PV systems and a reference power value. Three different references have been used with success in grid integration studies:

1. *Rating (in kVA) of the transformer* [7]: penetration level defined in this way is attractive in that it relates to a physical characteristic of the network which is relevant to grid integration issues of PV. Provided distribution networks follow comparable engineering rules (e.g., regarding the types of cables to be used), similar figures for such-defined penetration levels should yield similar results in terms of integration capability.
2. *Rating of the transformers feeding the area, after correcting the installed PV power with the nominal load:* $K_f \triangleq \frac{P_{DG,nom}-P_{load,min}}{P_n}$, where $P_{load\ min}$ is the minimal power load in the area, measured on a 15-min basis; P_n is the total nominal power of the HV/MV transformers feeding the area, and $P_{DG\ nom}$ is the total nominal power of distributed generators connected in the area. This definition is inspired by Italian regulations (TICA) [8], according to which an area could then be characterised as precarious if $K_f > 0$ and critical if $K_f > 0.9$
3. *Total capacity (on a feeder) that would be reached if all customers installed a system of optimal economic size from their point of view* [9]: calculating the penetration level with this definition requires much work, unless the customer profiles are very homogeneous. Its attraction is in the fact that a penetration level of 100% is the likely maximum value for all feeders

2.5 Hosting capacity

Hosting capacity characterises an electrical network rather than the PV generators installed on it. It is an absolute metric, defined as the maximum total peak power of PV systems that can be connected to the network under consideration while meeting key performance indices covering voltage, protection, power quality, and component loading [10]. There is no standard set of performance indices. EPRI for example uses 15 indices [11]. An accurate estimation of the hosting capacity is computationally intensive as it requires time series or stochastic analyses, the underlying principle being gradually to increase penetration levels until some violation occurs.

3 LOCAL TECHNICAL BARRIERS TO WIDER DEPLOYMENT OF PV INTO POWER GRIDS:

3.1 Voltage issues

In many grid configurations, overvoltage is the first issue to occur due to net injection of active power where consumption was expected. In typical residential underground, residential UK feeders, 30% of connected customers operating a PV system up to 4 kW are the maximum before voltage deviations outside the acceptable range (as per EN 50160 standard [12]) start occurring [13]. Physical grid reinforcement (installation of additional or larger cables) is generally necessary to eliminate this effect.

3.2 Harmonics

Harmonics can have detrimental effects such as increased device heating, malfunction of electronic equipment and protection, incorrect readings on meters, or triggering of resonant conditions. The probability of higher levels of total harmonic distortion (THD) on distribution networks increases with the introduction of PV [14]. Current harmonics are injected by PV inverters due to switching (pulsed-width modulation); they are influenced by the topology [15] and the controller [16] of the inverters. Cost pressure has limited progress in this area.

3.3 Reverse power flows and transformer loading

The loading of transformers can be affected by the PV penetration level as well as the voltage control methods, in case inverters supply reactive power compensation for supporting grid voltages. The increase in transformer overloading shows nonlinear characteristics with respect to the PV penetration. At low penetration levels, the transformer loading situation will not be affected by the PV. With increasing penetration levels, there could be a sharp increase of the transformer overloading due to the amount of active power generation as well as increased reactive power generation from inverters.

This problem can also be reflected from grid loss analysis. Studies in [9,17] show that the grid losses can be reduced in general at low penetration levels until a critical penetration level is reached. Afterwards the grid losses will increase more rapidly regardless of the control methods used, as shown in Figure 2.

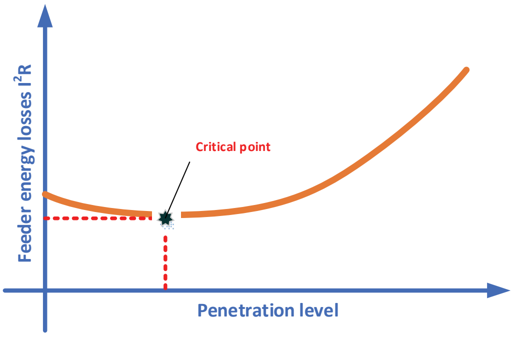

Figure 2: Evolution of grid losses with increasing PV penetration levels

4 SYSTEM-WIDE TECHNICAL BARRIERS

4.1 Reduction of system resilience

Deployment of PV systems can reduce the resilience of power systems in four ways:

- Generators connected through power inverters such as PV have lower inertia than conventional, rotating generators. This lower inertia reduces the available time for the system to respond to the sudden loss of large power plants
- PV systems can displace generators which are used for primary frequency control reserves
- Secondary control reserves are increasingly used due to power ramps [18]
- At high penetration levels of distributed PV systems, reverse power flows from the distribution level to the transmission system can frequently occur. These flows lead to an increased demand in re-dispatch of conventional power plants and revised procedures for congestion management.

Phase III of the Grid Integration of Variable Renewables project (GIVARIII) [19] evaluated the capacity of power systems to deal with rapid swings in supply and balance over time scales from one hour to 24 hours. The analysis showed that if flexibility is a priority for system operation, variable renewables can supply from 25% to 40% of annual electricity demand without any shortfall in flexibility.

4.2 Intermittency

All photovoltaic systems depend on the ambient solar irradiance for their energy generation. This irradiance is highly variable in time and in space and so is the generated power. Figure 3 illustrates this issue by showing how the power generation of a single PV system can vary over a few days. However, the rapid fluctuations are naturally mitigated when even a low number of generators and consumers are considered. This phenomenon is well known for loads, where it is characterised by the coincidence factor and can be used to optimise investments in power networks. The smoothing effect of aggregation further increases at larger spatial scales [20].

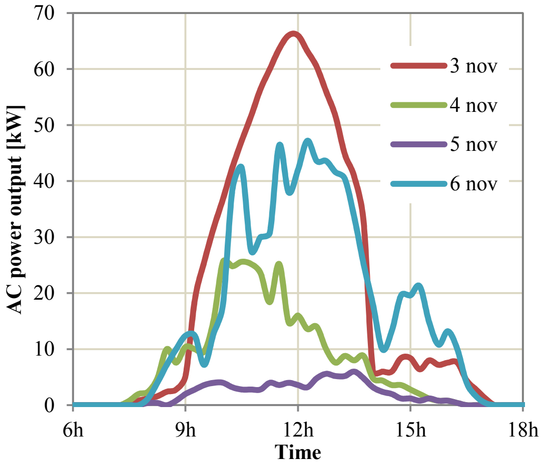

Figure 3: Power output of a single commercial PV power plant in five consecutive days of November 2014

4.3 Integration costs

The PV Parity project recently assessed grid costs associated with integrating solar PV into the EU grid (up to 15% generation in Europe by 2030) and found modest transmission costs [21]. In 2020 the cost is estimated at ca. 0.5 €/MWh for a PV penetration level of 240 GW, increasing to 2.8 €/MWh by 2030 at a PV penetration level of 485 GW. Reinforcing distribution networks to accommodate 485 GW of solar PV capacity, providing 15% of European electricity demand, would cost about 9 €/MWh by 2030.

5 SOLUTIONS FOR INCREASING THE PV HOSTING CAPACITY OF POWER GRIDS

5.1 Control of active power

The simplest form of active power control at the PV systems point of common coupling is to solely use the PV inverter for active power reduction. State-of-the-art solutions are static caps in feed-in power (e.g., the 70% cap as required by the German EEG from 2012) or DSOs sending active power feed-in limitation set values via a remote control interface. As compared to these approaches, volt/watt control of active power would be attractive by reducing active power only when local grid conditions require it (in case of over-voltages) and hence reducing the overall active power losses over all PV system within a certain grid section [22]. However this control will discriminate PV systems with technically unfavourable points of common coupling. In such a case, approaches for the compensation of lost energy need to be developed.

In addition, to support frequency control, droop curves can be implemented to automatically reduce active power with in case of frequency deviations (over-frequency response).

5.2 Control of reactive power

Reactive power supply/absorption for voltage support can significantly reduce grid extension costs. Initially, reactive power provision via PV inverters was established to mitigate high voltage magnitudes caused by reverse power flows. Numerous studies have shown the technical potential of reactive power for increasing the hosting capacity of a grid, although the technical effectiveness decreases with lower voltage levels [22–26].

Static reactive power provision is typically done in residential systems by setting a fixed, non-unity power factor for the inverter based on the installation point. Utility-scale PV systems typically come with a remote control interface that allows DSO to transmit reactive power set values to the PV plant.

Voltage dependent reactive power provision (also called volt/var control) is considered more advanced as it provides reactive power based on the locally measured voltage magnitude of the inverter. Various research projects are currently investigating the technical performance of such a control strategy with a focus on local stability issues [27–29].

In addition, PV systems and other generating units connected mostly to the medium- and high-voltage levels are required in some countries to inject reactive current in order to stabilize the grid in cases of voltage collapses [30,31]. This technical service is known as fault-ride through. Depending on the magnitude and duration of the voltage dip, the inverter is required to stay connected, inject reactive current or disconnect based on a characteristic that is part of each country’s technical specification.

5.3 Forecasting

Forecasting of PV production is necessary at different time and spatial scales for infrastructure planning, market operations, scheduling of other generators, or optimal control of storage and flexible loads. It relies on two aspects: modelling the performance of PV systems as a function of operating conditions, and predicting the weather parameters which affect the output of PV systems i.e., irradiance, ambient temperature, and wind speed. The techniques to forecast these meteorological variables can be divided into three mains groups:

- Numerical Weather Prediction (NWP) based on the numerical integration of coupled differential equations that describe the dynamics of the atmosphere and radiation transport mechanisms. Perez et al. [32] presented an extensive validation of short and medium term solar radiation forecast for various sites in the US.
- Statistical models based on methods to reconstruct the relations between the variables and past meteorological parameters (e.g. cloud ratio, air temperature, relative humidity, pressure etc.) or past observations. The most used models are based on machine learning methods (e.g. neural networks, support vector machines) or time-series based methods (e.g. ARIMA/X, SARIMA/X models).
- Hybrid models which combine for the forecast with statistical methods to correct site-specific effects through local measurements. The statistical models are essentially used to downscale the weather forecast.

Despite efforts to improve forecast techniques, they still incur high error rates. Observability and forecasting of PV generation will be covered in more details in future work by the European PV Technology Platform.

5.4 Combination with other renewable sources

Since the dependence of other renewable sources such as wind on time and location is different from that of PV, combining them helps mitigating the impact of variability. A remarkable example is the Greek island of Crete [33]. With an annual peak load of 640 MW, Crete is served by an isolated electric system with an average annual renewable electricity share of 23% (2013) and a maximum renewable capacity share of 44% (consisting of 186 MW wind power and 95 MW of PV power) compared to peak demand in 2012.

At present, during normal operation, PV plants provide power output without any restrictions, while wind parks contribute under constraint of the maximum allowable instantaneous renewable share, which is about 40%. If this value is reached, the power output of the wind parks is appropriately reduced.

5.5 Energy storage

At the building level, local storage can be used to store PV electricity produced in excess of the current demand. If correctly sized, it enables controlling the level of active power injected into the grid while making use of all the potential PV production [34]. The combination of smart storage systems and large photovoltaic systems can provide many functions at different levels of the electrical system, such as arbitrage, capacity firming, frequency and voltage control, capacity support. With storage, large PV power plants can provide ancillary services such as:

- Black start
- Primary/secondary response to unpredicted variations in demand and generation; the expected response time is in seconds to minutes.
- Contingency spinning reserve to respond to a contingency such as a generator failure; units must begin responding immediately and be fully responsive within 10 minutes;
- Replacement in case of the failure of a spinning unit into the network with a typical response time of 30 min to 60 min.

Reviews of the development status and suitability of different storage systems for grid applications are available [35]. Electrochemical batteries use chemical reactions, in two or more electrochemical cells, to create electric current by an oxidation-reduction process between the cell electrolyte and electrodes. Currently, the most commonly used electrochemical energy storage devices are based on lead, lithium, nickel, and sodium chemistries [36]. While they are suitable for energy storage on an hourly and daily basis, other energy storage solutions are necessary for weekly or seasonal variations. The main contenders are (pumped) hydro energy storage, compressed air storage, and chemical storage (power to gas) [35].

6 ENABLING FACTORS

6.1 Regulation

Successful integration of PV system into power grids will require a wide spectrum of regulatory measures. The interrelation between technologies and regulations requires both planning and flexibility. For instance, the increasing deployment of hybrid (PV+storage) technology might affect the competitiveness of existing PV-only systems with potentially negative impacts on their financial viability. Access to auxiliary service markets for PV producers – directly or through aggregators – could in this case help ensuring generators maximise the value of their production, which in turn occurs where appropriate pricing policies (real-time pricing, pricing by service) are in place.

The flexibility of the current wholesale market design should also be enhanced by reducing the duration of trading intervals and bringing gate closures closer to delivery time to facilitate the trading of electricity from variable sources. Tariff structures and metering schemes need to be revised as well to meet the needs of an increasingly decentralised generation fleet while ensuring full implementation of the EU target model. One such possible evolution is net metering. In its simplest form, net metering consists in counting positively in the electricity bill the power drawn from the grid and negatively the power injected from the building, while keeping the same fee structure. This approach has been attacked by utilities, in particular in the USA, for not providing adequate funding for the networks [37]. A more advanced net metering scheme is under experimentation in Cyprus for residential systems up to 3 kW$_p$ [38]. Thanks to high solar radiations, PV LCOE is lower in Cyprus than in any other EU country (about 0.08 €/kWh in 2012 for small systems[39], which makes it highly attractive against retail electricity prices (0.229 €/kWh [40]). Net consumption is calculated every two months. If it is negative (i.e., more energy was produced than consumed) the customer receives Renewable Energy Credits (RECs), which can be used against future positive net consumption bills in the year. In addition, an annual contribution to infrastructure costs is of 47.27 €/kW$_p$ is charged to the customer. The breakdown of this contribution is shown on Table 1.

Description	**Debit [€/kW$_p$]**	**Credit [€/kW$_p$]**
Operating expenses of Transmission System Operator (TSO-Cyprus)	1.48	
Ancillary Services	3.50	
Support of system for continuous supply of demand	13.82	
Charge for tertiary reserve	1.53	
Transmission Use of System Charge	3.98	
Distribution Use of System Charge – Medium Voltage	12.31	
Distribution Use of System Charge – Low Voltage	20.41	
Reduction due to less grid losses		20.00
Total amount for CERA's decision 909/2013	**37.03**	
Public Support Fund	2.19	
RES fund	8.05	
Total amount per year	**47.27**	

Table 1: Detailed analysis for net metering capacity charges per installed kWp

6.2 Communication standards

Communication is going to be part of the grid connection requirements in Europe [30]. It is also necessary for the coordination of the management and control mechanisms (e.g., battery management systems) of PV and storage systems. Some interoperability issues [41] must be therefore overcome:

- Standards are not mature in all areas and when they are vendors may not have implemented them yet
- Different, incompatible standards from various organisations or trade bodies are in competition for the same applications

Inverter manufacturers often have their own communication protocols and data formats. A common information model is necessary to ensure the interoperability and plug-and-play connection of PV plants. Current initiatives include SunSpec [42], IEEE 1547 [43], and IEC 61850-5 [44].

6.3 Planning rules

Electric grids are planned to meet the changes from generation and demand based on prediction of operational scenarios in the future. In order to determine a cost-effective solution for reinforcement, operational scenarios with more PV plants need to take into account the control capabilities from PV and other emerging technologies. Such capabilities are in particular the provision of reactive power capabilities. Voltage variations should be estimated under different scenarios for planning the connection of PV systems on a three- or single-phase system [45]:

- Worst case: all PV systems on one phase, e.g. L1
- Best case: ideal distribution over phases
- Residual unbalance: distribution over phases as good as practically possible at each node; voltage variations are then calculated based on the remaining unbalance at each node.

Planning procedures for distribution grids can also be improved using measured high-resolution load and PV profiles instead of synthetic profiles.

7 PV AS BUILDING BLOCK OF FUTURE POWER SYSTEMS

7.1 Reduced investments in existing grids

Increased electrification of the energy system and ageing infrastructures require major grid upgrades in developed countries. PV systems can reduced the need for investment in power networks thanks to three characteristics:

- They are distributed and can produce electricity close to the point of use
- In many locations, production occurs at times of high demand. . As a result PV systems, when adequately installed, can improve power quality (in particular voltage levels) at no cost to the DSOs [46] in stressed areas

- They are connected through active power converters (the inverters) which can support the local network even when the PV systems are not producing; an example is the compensation of reactive power through the so-called Q@night capability [47].

Currently, grid operators, both at transmission and distribution levels, have seen opportunities for utilising PV systems to solve different kinds of grid issues. Projects have been launched to develop solutions through technical and/or market measures [48].

7.2 Micro-grids

Micro-grids [49] consist of a combination of generation sources, loads and storage units that are connected to the distribution network through a single coupling point, and work – from the network perspective - as a single unit. A major characteristic of micro-grids is that they can operate either in parallel with the grid or in "island" mode (i.e., isolated from the grid) thanks to local control capabilities. Micro-grids can operate either in alternating current (AC) like the wider grids, or in direct current (DC) [50]. Indeed, both electrochemical storage and PV operate in direct current (DC) and an increasing share of the load in buildings (e.g., LED lighting, consumer electronics, computers) natively run on DC. As a result DC interconnection is getting traction, in particular within buildings [51,52]. Key challenges for the success of micro-grids are the development of appropriate control algorithms as well as protection and communication issues.

In isolated areas such as islands, remote villages, or mines, micro-grids are attractive to effectively combine PV generation with diesel engines. Indeed, many of these remote locations have a significant solar potential, yielding LCOE of PV electricity between 0.06 €/kWh and 0.10 €/kWh over a system lifetime of 20 years. In contrast, the fuel alone costs between 0.20 € and 0.30 € per kilowatt-hour of electricity from diesel generators. The objective when designing PV-diesel hybrid systems is therefore to reduce the use of diesel fuel by contributing to the demand and even reducing the running time of the diesel generators. Micro-grid technologies, though not yet standardised, can deliver these results while guaranteeing the stability and quality of power supply.

8 CONCLUSION

Although progress has been made in enabling PV integration over the past few years there is still a lot of room for improvement and solutions are reachable. Constructive co-operation between utilities, governments, regulators, and the PV industry is needed. An encouraging sign is the good alignment between the views of the Smart Grid Technology Platform, where DSOs play an important role, and those of the PV Technology Platform.

Grids can sustain unrestricted penetration of distributed generation provided that quality of supply is addressed at connection point through the capabilities of modern power electronics and distributed control. Ancillary services can fully complement faultless commitment of distributed, renewable energy sources in line with market requirements.

While the qualitative impact of PV on electric grids and of various technical approaches are clear, solid quantification is missing. More research is urgently needed to quantify both the achievable levels of PV penetration and the increase potential that existing concepts enable. Too often the integration of PV into power systems is seen as a threat to stability or affordability. We would like to highlight the opportunities that this integration represents. Indeed, PV systems can provide ancillary services and reduce the need for grid reinforcement in the face of increasing demand. At the centre of this potential lie advanced inverters and hybrid systems which combine PV with stationary storage or other power sources.

9 REFERENCES

[1] REN21, Renewables 2015 global status report. REN21 Secretariat, 2015.

[2] FS-UNEP Collaborating Centre for Climate & Sustainable Energy Finance, Bloomberg New Energy Finance, Global Trends in Renewable Energy Investment 2014. Frankfurt School of Finance & Management GmbH, 2014.

[3] E.ON, New corporate strategy: E.ON to focus on renewables, distribution networks, and customer solutions and to spin off the majority of a new, publicly listed company specializing in power generation, global energy trading, and exploration and production. E.ON SE, 2014.

[4] G. Masson *et al.*, Global market outlook for photovoltaics: 2014-2018. European Photovoltaic Industry Association, 2014.

[5] A.G. Martinez, *Network operation under high intermittent power generation*, 2011.

[6] European Commission, EU Energy in figures: statistical pocketbook 2014. Publications Office of the European Union, 2014.

[7] N. Efkarpidis *et al.*, in *3rd International Workshop on Integration of Solar Power into Power Systems*, 2013.

[8] Direzione mercati, Testo unico ricognitivo dell produzione elettrica. Autorità per l'energia elettrica il gas e il sistema idrico, 2014.

[9] A. Constantin, R. Dan Lazar, S. Bækhøj Kjær, Voltage control in low voltage networks by Photovoltaic Inverters - PVNET.dk. Danfoss Solar Inverters A/S, 2012.

[10] J. Kathan, *EERA Smart Grid R&D Workshop*, 2012.

[11] J. Smith, M. Rylander, C. Trueblood, *5th International Conference on Integration of Renewable and Distributed Energy Resources*, 2012.

[12] A. Klajn, M. Bątkiewicz-Pantuła, Standard EN 50160: Voltage characteristics of electricity supplied by public electricity networks. European Copper Institute, 2013.

[13] A. Navarro *et al.*, in *22nd International Conference and Exhibition on Electricity Distribution (CIRED 2013)*, 2013.

[14] M. Patsalides *et al.*, in *3rd IEEE International Symposium on Power Electronics for Distributed Generation Systems (PEDG)*, 2012, 709.

[15] E. Romero-Cadaval *et al.*, *IEEE Industrial Electronics Magazine*, 2013, **7**, 6.

[16] F. Iov *et al.*, in *7th International Conference on Power Electronics and Drive Systems PEDS '07*, 2007, P.

[17] M. Juamperez, G. Yang, S.B. Kjær, *Journal of Modern Power Systems and Clean Energy*, 2014, 1.

[18] J.H. Eto *et al.*, Use of Frequency Response Metrics to Assess the Planning and Operating Requirements for Reliable Integration of Variable Renewable Generation. Lawrence Berkeley National Laboratory, 2010.

[19] International Energy Agency, The Power of Transformation: Wind, Sun and the Economics of Flexible Power Systems. International Energy Agency, 2014.

[20] M. Rekinger *et al.*, Connecting the sun: solar photovoltaics on the road to large-scale grid integration. European Photovoltaic Industry Association, 2012.

[21] D. Pudjianto *et al.*, Direct Cost Analysis related to Grid Impacts of Photovoltaics. PV Parity, 2013.

[22] T. Stetz *et al.*, *IEEE Transactions on Smart Grid*, 2014, **5**, 2125.

[23] M. Braun *et al.*, in *24th European Photovoltaic Solar Energy Conference*, 2009, 3872.

[24] D. Mende *et al.*, in *2nd International Workshop on Integration of Solar Power into Power Systems*, 2012.

[25] C. Bucher, G. Andersson, L. Küng, in *28th European Photovoltaic Solar Energy Conference and Exhibition*, 2013, 4231.

[26] B. Bletterie *et al.*, in *25th European Photovoltaic Solar Energy Conference and Exhibition / 5th World Conference on Photovoltaic Energy Conversion*, 2010, 4828.

[27] P. Esslinger, Studie Q(U). Technische Universität München, 2012.

[28] B. Bletterie *et al.*, in *27th European Photovoltaic Solar Energy Conference and Exhibition*, 2012, 4574.

[29] M. Patsalides *et al.*, *IET Renewable Power Generation*, 2015.

[30] *ENTSO-E*, 2013.

[31] BDEW, Generating Plants Connected to the Medium-Voltage Network: Guideline for generating plants' connection to and parallel operation with the medium-voltage network. BDEW Bundesverband der Energie- und Wasserwirtschaft e.V., 2008.

[32] R. Perez *et al.*, *Solar Energy*, 2013, **94**, 305.

[33] J. Nikoletatos, S. Tselepis, Renewable Integration in Power Grids. IEA Energy Technology Systems Analysis Programme (ETSAP), 2013.

[34] J. von Appen, A.U. Schmiegel, M. Braun, in *27th European Photovoltaic Solar Energy Conference and Exhibition*, 3822.

[35] O. Teller *et al.*, Joint EASE/EERA recommendations for a European energy storage technology development roadmap towards 2030. European Association for Storage of Energy (EASE), 2013.

[36] Ricerca sul Sistema Energetico - RSE SpA, L'accumulo di energia elettrica. Il Melograno Editore srl, 2011.

[37] C. Martin, C. Chediak, *Bloomberg.com*, 2012.

[38] N. Philippou *et al.*, in *9th International Conference on Deregulated Electricity Market Issues in South Eastern Europe*, 2014, 37.

[39] S. Alberici *et al.*, Subsidies and costs of EU energy: annex 4-5. Ecofys, 2014.

[40] Eurostat, Electricity prices by type of user: Medium size households. European Commission, 2015.

[41] J. Hawkins, System Integration of Utility-Scale PV Plus Battery Storage: Interoperability and 'Lessons Learned'. Smart Grid Interoperability Panel (SGIP), 2014.

[42] SunSpec Alliance, SunSpec Alliance: Information Standards for Distributed Energy. SunSpec Alliance, 2014.

[43] IEEE SCC21, Interconnecting Distributed Resources with Electric Power Systems. IEEE, 2003, 1.

[44] TC 57, Communication networks and systems for power utility automation – Part 5: Communication requirements for functions and device models. International Electrotechnical Commission, 2013.

[45] M. Heidl *et al.*, morePV2grid: More functionalities for increased integration of PV into grid. Klima- und Energiefonds, 2013.

[46] W. Uturbey *et al.*, in *3rd Renewable Power Generation Conference*, 2014.

[47] SMA, Q at Night: Reactive power outside feed-in operation with the Sunny Central series CP XT, CP-JP and CP-US. SMA Solar Technology AG, 2011.

[48] C. Felix Covrig *et al.*, Smart grid projects outlook 2014. Publications Office of the European Union, 2014.

[49] N. Hatziargyriou *et al.*, *IEEE Power and Energy Magazine*, 2007, **5**, 78.

[50] J.J. Justo *et al.*, *Renewable and Sustainable Energy Reviews*, 2013, **24**, 387.

[51] IET Standards, Code of practice for low and extra low voltage direct current power distribution in buildings. The Institution of Engineering and Technology, 2015.

[52] D. Fregosi *et al.*, in *2015 IEEE First International Conference on DC Microgrids (ICDCM)*, 2015, 159.