Challenges and Solutions of Large-scale Photovoltaic Power Integration

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J-ERA Center Project
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PV power development

Effects for the electricity markets

Effects for the electricity grids

Key methodologies for PV Integration

IEA PVPS Task 14 “High-Penetration of PV Systems in Electricity Networks”
Content

- PV power development
- Effects for the electricity markets
- Effects for the nelectricity grids
- Key methodologies for PV Integration
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Global PV Trends

Figure 1 – Cumulative installed grid-connected and off-grid PV power in the reporting countries
High Penetration of PV in Electricity Grids?

- PV is unevenly distributed
- Only few countries account for around 75% of the global capacity installed *(End of 2012)*

<table>
<thead>
<tr>
<th>Country</th>
<th>Capacity (GW)</th>
</tr>
</thead>
<tbody>
<tr>
<td>DEU</td>
<td>32</td>
</tr>
<tr>
<td>Italy</td>
<td>25</td>
</tr>
<tr>
<td>JAP</td>
<td>7</td>
</tr>
<tr>
<td>USA</td>
<td>7</td>
</tr>
<tr>
<td>CHINA</td>
<td>7</td>
</tr>
<tr>
<td>ESP</td>
<td>4.5</td>
</tr>
<tr>
<td>BEL</td>
<td>2.6</td>
</tr>
<tr>
<td>AUT</td>
<td>0.4</td>
</tr>
</tbody>
</table>

* Source: www.EPIA.org, Market report 2011
** Erneuerbare Energien Österreich: Marktstudie 2012
• Example: Germany
- **Germany 1994** Ms. Merkel: “*Sun, Wind and Water will never be able to cover more than 4 % of the German electricity needs.*”

1994 bis 1998 Bundesministerin für Umwelt, Naturschutz und Reaktorsicherheit (Kabinett Kohl V)

- **Germany today:**

  *Official targets:*
  - 35% by 2020
  - 80% by 2050

*Renewables, especially PV are frequently completely underestimated*
Increase of Renewable Energy Sources in Germany 1990 – 2011

- Natural Gas: 26 GW
- Lignite: 21 GW
- Hard Coal: 27 GW
- Nuclear: 21 GW

Source: [BRAUN] and http://www.umweltbundesamt.de
Status: April 2011

June 2011:
> 900,000 plants about 80% of the capacity in low voltage grids

Source: [Martin BRAUN, FhG IWES, Kassel]
Electric Solar Energy contributes...

- by the year 2050: 24%
- until year 2100: 63%

... to the global energy production
Cost reduction of PV Systems – 65% since 2006

Price for end users
(turn key smaller than 100kWp)

Chinese c-Si PV module Prices,
Source: Reconsidering the economics of PV Power,
M.Bazilian et al., 2012

Figure 2: Chinese c-Si PV module prices ($/W): Note the change in the slope of the curve since 2008.
New installed Power in Europe 2011

Wind in Europe: September 2012: 100 GW
Photovoltaic: ~ 65 GW

Quelle: Wind in power, 2011 European statistics, February 2012, European wind Energy Association
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New Renewables in the Electricity System – Example: Germany

Maximum Load: 80 GW
Minimum Load: 40 GW
PV installed: ~ 32 GW
Wind installed: ~ 31 GW
Typical Load in German grid (working day, autumn)

Results:

- Gas and Pump-Hydro Power Plants have significantly reduced working hours, reduced economic performance

  … but are needed if there is no sun (and wind…)

- Compensation payments are under discussion

- The current electricity pricing at exchange is under discussion
Power exchange: relation of the hourly mean values of the peak hours to the annual mean value from 2007 to May 2012
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Characteristics of PV power generation

- Fluctuating generation
  - Daily profile
  - Seasonal profile
  - Variability
- Typical system size
  - Many small scale (domestic) installations
  - Large scale installations
- Connection predominantly at LV grid - Inverter connection (no transformer)
- Heavily dependent on support incentives – in only a few markets / countries
- Frequently linked to buildings
- Suited for new decentralized storage solutions
Characteristics PV power generation
Impact on the grid

- **Additional power flows**
  - additional loading of grid components
  - grid extension required (transformers & lines)

- **Reverse power flows**
  - voltage rise in distribution grids
  - grid extension and voltage control devices required

- **Grid stability (frequency and voltage)**
  - protection and control settings often cause additional destabilization in abnormal situations and little support in normal operation situations
  - traditional/conventional power system has to guarantee stability

→ Smart PV integration required !!!
Impact on the grid

Power and safety quality issues

- Harmonics
- DC Injection
- Unintentional Islanding

... are mainly solved
Intelligent voltage range management

(A) What can be expected without intervention

U_max

plot of maximum voltage

voltage climbs above upper limit

U_min

plot of minimum voltage

voltage falls below lower limit

January

December

(B) Solutions with an active distribution grid

U_max

U_min

January

December

A shows that without intervention the actual voltage strays outside the permissible limits.
B shows how the voltage range is adjusted as the need arises – made possible through active intervention influencing the actual voltage in real time.
Technical solutions to meet overvoltage problems caused by PV in distribution networks

<table>
<thead>
<tr>
<th>Category</th>
<th>Nb.</th>
<th>Technical solution</th>
</tr>
</thead>
<tbody>
<tr>
<td>DSO</td>
<td>1</td>
<td>Network Reinforcement</td>
</tr>
<tr>
<td></td>
<td>2</td>
<td>On Load Tap Changer for MV/LV transformer</td>
</tr>
<tr>
<td></td>
<td>3</td>
<td>Advanced voltage control for HV/MV transformer</td>
</tr>
<tr>
<td></td>
<td>4</td>
<td>Static VAr Control</td>
</tr>
<tr>
<td></td>
<td>5</td>
<td>DSO storage</td>
</tr>
<tr>
<td></td>
<td>6</td>
<td>Booster Transformer</td>
</tr>
<tr>
<td></td>
<td>7</td>
<td>Network Reconfiguration</td>
</tr>
<tr>
<td></td>
<td>8</td>
<td>Advanced Closed-Loop Operation</td>
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<tr>
<td>PROSUMER</td>
<td>9</td>
<td>Prosumer storage</td>
</tr>
<tr>
<td></td>
<td>10</td>
<td>Self-consumption by tariff incentives</td>
</tr>
<tr>
<td></td>
<td>11</td>
<td>Guaranteed self-consumption</td>
</tr>
<tr>
<td></td>
<td>12</td>
<td>Direct voltage control by PV inverter Q(U) P(U)</td>
</tr>
<tr>
<td></td>
<td>13</td>
<td>Indirect voltage control by PV inverter Q(P)</td>
</tr>
<tr>
<td>INTERACTIVE</td>
<td>14</td>
<td>Demand response by market price signals</td>
</tr>
<tr>
<td></td>
<td>15</td>
<td>Demand response by local price signals</td>
</tr>
<tr>
<td></td>
<td>16</td>
<td>SCADA + direct load control</td>
</tr>
<tr>
<td></td>
<td>17</td>
<td>SCADA + PV inverter control (Q only)</td>
</tr>
<tr>
<td></td>
<td>18</td>
<td>SCADA + PV inverter control (Q and P)</td>
</tr>
<tr>
<td></td>
<td>19</td>
<td>Wide area voltage control</td>
</tr>
</tbody>
</table>

Source: EU Project PV GRID
Characteristics of PV power generation

- **PV production** frequently meets times of high load in networks

- **Reduction of network losses** due to more local generation and therefore decreased power transmission

- **More transmission capacity** opens space for other transmission services

- **Active network services** from multifunctional photovoltaic inverters can support the local network management
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- **Key methodologies for PV Integration**
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PV Power Planning tools

- **Analysis of hosting capability** of PV in local distribution grids by the means of Load and PV profiles
  - Load profiles from 1 sec measurements
  - P and Q of all phases
  - PV profiles from 1 sec \{G,T\} measurements
  - Six representative days.
  - I-V curve model from EN 50530

Source: Benoit Bletterie, AIT
PV Power Prediction tools

- **Parameter:**
  - horizontal global irradiation
  - PV-Power

- **Forecast Timeframe:**
  - Very short-term (0-6h)
  - Short-term (6h-72h)
  - Medium and Long-term (seasonal)

- **Forecast Area:**
  - Point
  - Area (regional weighting)
PV power active management and control

- **Remote dispatch**
  - Control PV generation to a specified % of nominal power rating (Remote Dispatch for security actions)
  - Standardized control and communication interfaces required

- **Support Frequency Control**
  - Automatically reduce active power with frequency deviations (Over Frequency Response)
  - Integrate harmonized frequency stabilization functions!

- **Support Voltage Control**
  - Reactive power supply/absorption for voltage support
  - Reduces grid extension costs significantly

- **LVRT Fault Ride Through**
  - Supply reactive current during fault ride-through period,
  - No disconnection during grid faults

Source: [BRAUN], BDEW, SMA
Grid Interconnection Assessment

- Harmonized and straightforward administration procedures
- Clear responsibilities of DNOs and customer
- Transparent planning and assessment

**EU Project PV GRID: PV GRID** is a project funded by the European Commission’s Intelligent Energy for Europe programme. It will run from May 2012 until October 2014 and its aim is to contribute to overcoming the bureaucratic barriers holding back the large-scale integration of Photovoltaic (PV) power into the electricity Distribution Systems (DS) across Europe. ([www.pvgrid.eu](http://www.pvgrid.eu))
Technical standards and interconnection requirements

• **Adaption of technical requirements**
  – according to changing general conditions
  – e.g. 50,2 Hz (VDE0126-1-1) -> frequency control (AR N4105)
  – Harmonize testing procedures

• **Inconsistent requirements**
  – Growing complexity and diversity of requirements may create an increasing barrier to effectively apply the potential of new inverter functionalities in practice

• **International exchange of experiences and harmonized standards (e.g. IEEE 1547)**

Source: VDN 2007, translation SMA
Integration Testing of PV systems in laboratory environment

- Simultaneous testing of power and control interfaces of DR components under controlled environment conditions

- DER component laboratory with highly flexible grid and primary energy source (e.g. PV) emulation
  - LV up to 800 kVA

- Power-Hardware-in-the-loop environment

AIT Smartest Laboratory
(to be inaugurated April 2013)
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IEA organisation structure
IEA Implementing Agreements

• > 40 current IEA Implementing Agreements
• Participants are OECD countries, increasingly non-OECD countries and industry organisations

• Nearly 500 participating institutions

• Collectively, they mobilise annually an estimated US$120 million to US$150 million

• “PVPS one of the most active, successful programmes”
IEA PVPS

Global co-operation towards sustainable deployment of photovoltaic power systems

Stefan Nowak, Chairman IEA PVPS

200 Experts in 7 projects (“Tasks”)
IEA PVPS – Task 14
High Penetration of PV Systems in Electricity Networks

„High Penetration PV”
- High penetration situation exists if additional efforts will be necessary to integrate the dispersed generators in an optimum manner.

Aim
- Develop and verify technical requirements for PV to achieve high penetration levels of distributed renewable energy systems on the electric power system
- Enable the active role of PV systems related to energy management and system control of electricity grids

Outcomes
- provide access to more transparent technical analyses in order for industry, network operators, energy planners as well as authorities in the energy business to decide on steps to be taken and strategies to be developed
- provide comprehensive international studies for high penetration PV including objective and neutral high-quality information
IEA PVPS – Task 14
High Penetration of PV Systems in Electricity Networks

- Aspects related to the fluctuating nature of **PV in relation to electricity demand** focusing on the consumer behavior to be better linked to the generation profile

- Effects on PV generation to the **local distribution grid** as well as to the **general electricity system**

- **Multifunctional inverters** dealing with requirements for such devices at high PV penetration aiming the smart interface between the generator and the electricity network

- Convincing case studies, **modeling and simulation**
IEA PVPS – Task 14
High Penetration of PV Systems in Electricity Networks

• 15 Countries

- Utilities/DNOs
- Industry/Manufacturers/Consultants
- Applied research
- Universities
- Agencies

Task 14 – First Results

High Penetration Case Studies

- Distribution grid case studies
  - Germany
  - USA
  - Belgium
  - …

- Overall power system studies
  - Japan
  - USA
  - Italy
  - …

Source: E.on Bayern/Fraunhofer IWES
Source: SMUD/NREL
Source: NREL
Source: Y.M. Saint Drenan/Fraunhofer IWES

Length of Feeder: 22 km / 13.7 Miles

Open Switch
Task 14 – dissemination and interaction with key stakeholders

- Successful series of Task 14 High Penetration PV Workshops:
  - Sept. 2010: Joint Task 1/14 workshop EUPVSEC/ WCPEC in Valencia, **Spain**
  - Dec. 2010: Task 14 workshop, Golden, CO, **U.S.A.** Hosted U.S. DoE, NREL and SEPA
  - May 2011: Task 14 utility workshop, Lisbon, **Portugal**, Hosted by EDP
  - Oct. 2011: Task 14 Utility and Research workshop, Beijing, **China**, hosted by the IEE, Chinese Academy of Sciences
  - May 2012: Task 14 High penetration PV workshop, Kassel, **Germany**, Hosted by SMA
  - Nov. 2012: Task 14 High penetration PV workshop, Tokyo, **Japan**, hosted by NEDO

- Presentations available at [www.iea-pvps.org](http://www.iea-pvps.org)
The future of the electricity system
8. Internat. SMART GRIDS WEEK SALZBURG 2013

- 14.- 17. Mai 2013
- 300 Experts expected
- Language: English/German
Summary

• PV is on its way to become a pillar in electricity supply
• PV will significantly change the electricity markets

Key methodologies for Large-scale PV Power Integration
  – PV Power Planning tools
  – PV Power Prediction tools
  – PV power active management and control
  – Grid interconnection assessment
  – Technical standards and interconnection requirements
  – Integration Testing of PV systems in laboratory environment & in the field

• By improving the knowledge of LV networks, additional reserves can be made available for PV.

• IEA-PVPS Task 14 will act as a collaboration platform for international experts on the subject of high penetration PV
Thank you for your attention!
Key methodologies for PV Integration
-> Testing of PV systems in the field

- MetaPV  
  www.metapv.eu

- MorePV2grid  
  www.ait.ac.at/.../smart-grids/morepv2grid/

- PVIntegrated  
  www.pv-integrated.de

- Modellregion Salzburg  
  www.smartgridssalzburg.at

- High Penetration Solar Demonstration projects,  
  https://solarhighpen.energy.gov/

- Connecting the sun, EPIA, 2012
References / Acknowledgement

• [BRAUN] Prof. Dr.-Ing. Martin Braun „Is the Distribution Grid Ready to Accept Large-Scale Photovoltaic Deployment?”
26th EU PVSEC, 2011, Fraunhofer IWES, Universität Stuttgart

• [BLETT] B. Bletterie, M. Heidl, A. Abart, “Understanding the effects of unsymmetrical infeed on the voltage rise” - 26th EU PVSEC, 2011, ©AIT


• Christoph Mayr and Roland Bründlinger, Operating Agents of IEA PVPS Task 14
  Roland.bruendlinger@ait.ac.at
  Christoph.mayr@ait.ac.at
Denmark

- **1980: Central generation**
- **2000: Centrale and decentral generation**

16 powerplants

Quelle: www.ens.dk

16 powerplants

+ 1000 CHP - Plants

+ 6000 Windturbines
In weniger als 30 Jahren wurde der Ertrag von Windenergieanlagen um mehr als das 500-fache gesteigert.

<table>
<thead>
<tr>
<th>Jahr</th>
<th>Nennleistung</th>
<th>Rotordurchmesser</th>
<th>Nabenhöhe</th>
<th>Jahresenergieertrag</th>
</tr>
</thead>
<tbody>
<tr>
<td>1980</td>
<td>30 kW</td>
<td>15 m</td>
<td>30 m</td>
<td>35.000 kWh</td>
</tr>
<tr>
<td>1985</td>
<td>80 kW</td>
<td>20 m</td>
<td>40 m</td>
<td>95.000 kWh</td>
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<tr>
<td>1990</td>
<td>250 kW</td>
<td>30 m</td>
<td>50 m</td>
<td>400.000 kWh</td>
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<tr>
<td>1995</td>
<td>600 kW</td>
<td>46 m</td>
<td>78 m</td>
<td>1.250.000 kWh</td>
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<tr>
<td>2000</td>
<td>1.500 kW</td>
<td>70 m</td>
<td>100 m</td>
<td>3.500.000 kWh</td>
</tr>
<tr>
<td>2008</td>
<td>6.000 kW</td>
<td>126 m</td>
<td>135 m</td>
<td>ca. 20.000.000 kWh</td>
</tr>
</tbody>
</table>
Documents of the European Technologyplatform (ETP) Smart Grids
Consultative process that enable interconnection of renewable to the electricity grid, set prices for renewable generation technologies and establish net metering rules.

How are issues resolved, those related to provision of support to peak load, corresponding reserve capacities and quick response in case of interruption in supply of electricity to the network from RES in order to ensure security of supply?

What are common technical and economic problems of PV technology integration in the power grid, and problems in the local network that appear when PV is connected to the distribution network in connection with distribution network configuration for transmission of power in one direction? Studying problems and consequences (including financial ones) of strengthening of the distribution system, shifting costs to strengthening of the distribution system, and also additional network investment costs.

Impact of methods of allocation of costs associated with proliferation of renewable production for the purpose of concealing the real cost of the resource and inefficient investment decisions.