Grid Integration Challenges of Renewable Energy Sources and Prospective Solutions

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Topics and Questions of this Talk

- Complexity of Power System Processes

- On-Going Transformation of Power Systems (CH, DE, Europe)
  - Impacts of Renewable Energies
  - Energy Transformation («Energiewende»)
  - Impacts of Liberalization and Power Markets

- Grid Integration Challenges for Power Systems with High Shares of Fluctuating Renewable Energy Sources (RES)
  → What are the challenges for grid integration of wind & PV units?
  → What are the opportunities of RES deployment?
  → What are the opportunities for control engineering («smartness»)?
  → What is the role of energy storage?
  → Power System Planning: «Hard Paths versus Soft Paths» (A. Lovins)

- Prospective Solutions
Structure of this Talk

- Complexity of Power System Processes
- Trends & Challenges in Power System Operation
- Role of Operational Flexibility in Power Systems
- Modeling and Analysis of Power Systems and their Operation
- Conclusion
Structure of this Talk

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Complexity of Power Systems

Complexity along several dimensions

- **Time** (milli)seconds (e.g. frequency inertia, frequency & voltage control), minutes (e.g. secondary/tertiary frequency & voltage control), hours/days (e.g. spot market-based plant/storage scheduling), months/years (e.g. seasonal storage, infrastructure planning).

- **Space** 1'000+ km, e.g. interconnected continental European grid (Portugal – Poland: 3’600 km, Denmark – Sicily: 3’000 km).

- **Hierarchy** from distribution grid (e.g. 120/240 V, 10 kV) to high-voltage transmission grid (e.g. 220/380 kV).
Complexity of Power Systems

PAST – Traditional view

Coal  Nuclear  Gas  Hydro

conventional Generation [+/-]

Fully dispatchable
~99% of all generation

Transmission Grid
(Line rating & Voltage/Frequency constraints)

Power Flow Control
(e.g. line switching)

Loads (assumed non-controllable)

Observable & well predictable
Interruptible loads by manual or static control means
(large industrial loads, hot water boilers)

[+/-]: Power regulation up/down possible.

Hydro Storage only

Fully dispatchable
(energy constraints)
~10% of peak load

Storage [+/-]
Complexity of Power Systems

PRESENT & FUTURE – high RES shares & Smart Grid Vision

(During capacity values of year 2011)

Transmission Grid

(Line rating & Voltage/Frequency constraints)

Coal Nuclear Gas Hydro Biomass

Fully dispatchable ~60% of all generation

var-RES Generation [+/-]

Wind Solar PV

Time-varying dispatchable ~40% of all generation

Storage [+/-]

Hydro Storage, Batteries, Flywheels, …

Soon >10% of peak load

Non-controllable Loads

controllable Loads [+/-]

(price-responsiveness: Demand Response)
(control signal-driven: Demand Side Participation)

Increase of controllable loads
(faster response times, automatic control)

[+/-]: Power regulation up/down possible.

Power Flow Control (incl. FACTS)
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Increasing fluctuating RES deployment = Stochastic power in-feed

- Germany 2011: 53.9 GW power capacity ≈ 63% of fully dispatchable fossil generation. (Wind+PV) 63.6 TWh energy produced ≈ 12.5% of final electricity consumption.
- Wind+PV: Still mostly uncontrolled power in-feed – Hydro: well-predictable power in-feed.

Mitigation Options

- Improvement of Controllability: Wind/PV unit curtailment implemented in some countries.
- Improvement of Observability: More measurements and better predictions of PV and wind power in-feed (state estimation & prediction).

Data:
- P_e: Wind 29.1GW, PV 24.8GW, Hydro 4.8GW – E_e: Wind 44.8TWh, PV 18.8TWh, Hydro 19.6TWh – Germany Final Electricity Consumption (2011): ≈510TWh estimated – Fully dispatchable (fossil+nuclear) generation: ≈ 85GW

Sources:
- BaSt 2012, IEA Electricity Information 2011, own calculations

2016 (Wind+PV):
- ≈ 86 GW_{el} power capacity
- ≈ 120 TWh_{el} generated

Trends and Challenges
Increasing fluctuating RES deployment = Stochastic power in-feed

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Sources: BaSt 2012, IEA Electricity Information 2011, own calculations
RES Integration challenges are on different time-scales (Germany, 2010)

**Hourly Power Infeed Profile**

- Buffering of RES In-feed and Load Demand Peaks
- Requires fast ramping capability

**Monthly Power Infeed Profile**

- Accommodation of seasonal changes in RES in-feed and Load demand
- Requires back-up capacity (and some day seasonal storage)
Recent record: 22GW PV peak on 25 May 2012 (>33% of average load demand)

Angezeigter Zeitraum: 25.05.2012, 00:00 Uhr - 25.05.2012, 23:59 Uhr
Letzte Aktualisierung: 26.05.2012, 04:00:21 Uhr

Source: EEX Transparency website

Grid integration becomes more challenging as wind and PV deployment continues.
Challenges of Wind & PV (but also Load Demand) Forecasts

Wind Power In-Feed (DE 24.05.2011)

Wind Power In-Feed (DE 31.05.2011)

PV Power In-Feed (DE 30.05.2011)

PV Power In-Feed (DE 31.05.2011)
RES Integration challenges in Switzerland (ETH Scenario 2050)

Fluctuating Power In-Feed:  
1. Generation Capacities?  
2. Energy Storage Capacities?  
3. Invisible Ceiling for Operational Flexibility?

Electricity Consumption [MW] -- Scenario 2050
PV [MW] -- Scenario 2050
Wind [MW] -- Scenario 2050

Power Surplus
Power Shortage

ETH Zurich Energy Scenario 2050: Potential Swiss Load Demand, Wind and PV In-feed using (June/July-Week).
Trends and Challenges

Impacts on Power Markets (Merit-Order Effect of RES Generation)

- **Wind power in-feed** (zero marginal cost) shifts supply curve to the right

- **Result**
  Reduction of average spot price level

- **Long-term impact**
  Risk for conventional generators (recovery of investment)

Wind in-feed reduces spot prices (neg. correlation between wind in-feed and spot price).

Source: Hildmann, Ulbig, Andersson, IEEE EEM 2011
Trends and Challenges

Impacts on Power Markets (Merit-Order Effect of RES Generation)

- PV power in-feed causes reduction of spot price spread $\zeta$ (zero marginal cost, zero price bid in supply curve)

- Net energy arbitrage potential $\Delta_{net}$ between peak and off-peak hours significantly reduced

<table>
<thead>
<tr>
<th>Year</th>
<th>$\zeta$</th>
<th>$\Delta_{net}$ [(\frac{\text{\euro}}{\text{MWh}})]</th>
<th>$P_{\text{base}}^{\text{spot}}$ [(\frac{\text{\euro}}{\text{MWh}})]</th>
</tr>
</thead>
<tbody>
<tr>
<td>2006</td>
<td>1.59</td>
<td>17.06</td>
<td>50.79</td>
</tr>
<tr>
<td>2007</td>
<td>1.64</td>
<td>15.00</td>
<td>37.99</td>
</tr>
<tr>
<td>2008</td>
<td>1.51</td>
<td>17.12</td>
<td>65.76</td>
</tr>
<tr>
<td>2009</td>
<td>1.46</td>
<td>8.09</td>
<td>38.85</td>
</tr>
<tr>
<td>2010</td>
<td>1.33</td>
<td>3.71</td>
<td>44.49</td>
</tr>
</tbody>
</table>

Source: Hildmann, Ulbig, Andersson, IEEE EEM 2011

PV in-feed flattens spot price curve during peak hours, reducing energy arbitrage yield.
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Sources of Operational Flexibility in Power Systems

Available Operational Flexibility

- **Conventional Power Units** (incl. Biomass/biogas)
  - fully controllable [+/-] (depending on unit type)

- **Energy Storage**
  - fully controllable [+/-] (energy constraint, hydro power: seasonal effects)

- **Demand Side Participation (DSP)**
  - fully controllable [+/-] if grid-connected (energy constraint)

- **Wind / Solar Power Units**
  - curtailable [-] or time-varying controllable [+/-]

- **Industrial loads**
  - curtailable [-] or fully controllable [+/-] (production dependent)

- **Thermal loads in residential sector**
  - curtailable [-] or fully controllable [+/-] (energy constraint)

- **Time-varying available storage**
  - fully controllable [+/-]

- **Fully dispatchable storage**
  - Storage lake / Pump storage unit, CAES, stationary batteries, ...
Sources of Operational Flexibility in Power Systems

Electricity Consumption [MW] -- Scenario 2050
PV [MW] -- Scenario 2050
Wind [MW] -- Scenario 2050

Hydro Pump Storage CH
1.7GW, 50-100GWh
η = 75–80%

PHEV/EVs
0.3 GW, 1.2 GWh
η = 80–90%

Heat Pumps
0.7 GW, 0.6 GWh

Fridges/Freezers
1GW, 0.1 GWh

DSM (Electric Boiler)
2.5GW, 1GWh

ETH Zurich Energy Scenario 2050: Potential Swiss Load Demand, Wind and PV In-feed using (June/July-Week).

[ENTSOE 2011, EEX 2011]
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Consideration of interactions of power system units and the electricity grid, i.e. power injected into the grid or power demanded from the grid, is not giving the whole picture.

- Which of these units are storages (and thus energy-constrained)?
- Which of these units provide fluctuating power in-feed?
- What controllability and observability (full / partial / none) does an operator have over fluctuating generation and demand processes?
One Power Node

**Demand/Supply-side**
- **Provided energy** (water, wind, fuel...)
  \[ \xi > 0 \]
- **Demanded energy** (heat, light, ...)
  \[ \xi < 0 \]
- **Spilled energy** (wind, water, ...)
  \[ w > 0 \]
- **Unserved load**
  \[ w < 0 \]

**State-Descriptor Form**
\[ C_{SOC,i} \dot{x}_i = a_i x_i + b_i^T u \]

<table>
<thead>
<tr>
<th>Storage capacity</th>
<th>State-of-charge (SOC)</th>
</tr>
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<tbody>
<tr>
<td>( \times )</td>
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</tbody>
</table>

**Power out-feed from grid**
\[ C_i \dot{x}_i = \eta_{load_i} u_{load_i} - \eta_{gen_i}^{-1} u_{gen_i} + \xi_i - W_i - v_i \]

**Power in-feed to grid**

**Efficiency factors**

**Provided / demanded power**

**Internal storage losses** \( v(x) \)

**Shedding term**
Examples of Power Node Definitions

**General formulation:**

\[ C_i \dot{x}_i = \eta_{load_i} u_{load_i} - \eta^{-1}_{gen_i} u_{gen_i} + \xi_i - w_i - v_i \]

- Fully dispatchable generation
- No load, no storage \((C)\)
- Fuel: natural gas \((\xi > 0)\)

- Time-dependent dispatchable generation, if wind blows, \(\xi \geq 0\), and if energy waste term \(w \geq 0\)
- No load, no storage \((C)\)
- Fuel: wind power \((\xi > 0)\)
Examples of Power Node Definitions

**General formulation:**

\[ C_i \dot{x}_i = \eta_{load_i} u_{load_i} - \eta_{gen_i}^{-1} u_{gen_i} + \xi_i - w_i - v_i \]

- Fully dispatchable generation (turbine) and load (pump)
- Constrained storage \((C \approx 8 \text{ GWh})\)
- Fuel: almost no water influx \((\xi \approx 0)\)

**Goldisthal Hydro Pumped Storage, Germany**

- Fully dispatchable generation (turbine), but no load (pump)
- Large storage \((C \approx 1000 \text{ GWh})\)
- Fuel supply: rain, snow melting \((\xi > 0)\)

**Emosson Storage Lake, Switzerland**

\[ C_i \dot{x}_i = \eta_{load_i} u_{load_i} - \eta_{gen_i}^{-1} u_{gen_i} \]

\[ C_i \dot{x}_i = -\eta_{gen_i}^{-1} u_{gen_i} + \xi_i \]
Examples of Power Node Definitions

General formulation:

\[ C_i \dot{x}_i = \eta_{\text{load}} u_{\text{load}} - \eta_{\text{gen}}^{-1} u_{\text{gen}} + \xi_i - w_i - v_i \]

- Dispatchable generation, but no load
- Storage function dependent on geography, \( C \in [0, \ldots, \text{GWh, TWh}] \)
- Fuel (\( \xi \)): water influx from river, (\( \xi > 0 \))
- Waste (\( w \)): water flow over barrage (high water-level) or intentional water diversion

\[ C_i \dot{x}_i = -\eta_{\text{gen}}^{-1} u_{\text{gen}} + \xi \text{ water inflow} - w_i \]

- Dispatchable generation and load
- Constrained storage (\( C \approx \text{GWh range} \))
- Fuel (\( \xi_{i,k} \)): water influx from upper basin and other inflows (\( \xi_{i,k} \geq 2 \))
- Waste (\( w \)): water discharge into lower basin (or river)
- Loss (\( v \)): evaporation from bassin

\[ C_i \dot{x}_i = \eta_{\text{load}} u_{\text{load}} - \eta_{\text{gen}}^{-1} u_{\text{gen}} + \sum_{k} \xi_{i,k} - w_i - v_i \]
Simplified Functional Representation of a Power System

Modeling of Interaction with Electricity Grid only

Electricity Generation (no embedded storage)

$u_{\text{gen}}$

Electricity Generation (embedded storage)

$u_{\text{gen}}$

Electricity Bulk Storage

$u_{\text{load}}$

Electricity Demand (no embedded storage)

$u_{\text{load}}$

Electricity Demand (embedded storage)
(More) Complete Functional Representation of a Power System
Simulation Results – Predictive Power Dispatch (Case Study Germany)

- **Simulation Period** May 2010 (30% Wind, 50% PV, no DSP)
- **High Temporal Resolution** $T_{\text{pred.}} = 72\text{h}, T_{\text{upd.}} = 4\text{h}, T_{\text{sample}} = 15\text{min.}$
- **Calculation Time** $\approx 1\text{min.}$

![Diagram showing simulation results with curves representing different power sources and storage saturation]

- **Curtailment of Wind or PV Power Infeed**

- **Storage saturation**
Assessment of Flexibility
General Simulation Approach

- Predictive power dispatch for full-year simulations
- High temporal resolution (15min.) – 1 year / 15min. ≈ 35’000 sim. steps
- Parallel calculation of 10-1000s scenarios (perfectly parallel task)

Parallel Calculation (2-12x)

- Scenario Creation (10...1000)
- Yearly Power Dispatch Simulations (high temporal resolution)
- Balance Term Assessment

Power Systems Specs (Power Plants, Merit Order, Control Reserve Requirements)

Grid Topology

Time Series (Wind, PV, Water In-feed, Load)

Assessment & Analysis Data (Fossil Fuel Usage, Storage Cycling, Curtailment, ...)

Data Mining Challenge!
Assessment of Flexibility – Curtailed Renewable Energy in Germany

0-50% Wind Energy, 0-50% PV Energy, Full-Year 2011 simulations
only existing hydro storage, copperplate grid model, no export, no DSP

Curtailed RES Energy
(in % of total available RES Energy)

PV Power Deployment

Wind Power Deployment

0 5 10 15 20 25 30 35 40 45 50

0 5 10 15 20 25 30 35 40 45 50
Assessment of Flexibility –
Curtailed Renewable Energy in Germany

20% Wind Energy, 10% PV Energy (EU-NREAP Goals), Full-Year 2011 simulations
only existing hydro storage, copperplate grid model, no export yet, no DSP

Storage Capacity today
\( \pi \approx 7 \text{ GW} \) (8% of peak load)
\( \varepsilon \approx 40 \text{GWh} \) (~6h)

Increasing Energy Rating \( (\varepsilon) \)
Increasing Power Rating \( (\pi) \)
Simulations of Swiss Power System

Modeling and Simulation of Swiss Power System using Power Nodes

- Full-Year Simulations based on ETH 2050 Scenario (14 TWh PV, 3 TWh Wind, 39 TWh Storage Lake and Run-of-River Hydro, 78 TWh Load demand)

- Aggregation of 7 different Power Node types (load demand, wind & PV units, hydro storage lakes, run-of-river, pumped hydro storage, backup generation)
Simulations of Swiss Power System

Flexibility Electricity Production from Hydro Units

- Some flexibility for run-of-river plants observable (higher production levels during peak hours).
- Storage lakes are highly flexible producers when lakes are (energywise) neither empty nor full.
Simulations of Swiss Power System using Power Nodes

Modeling and Simulation of Swiss Power System (PHS: 1.7 GW, 50GWh)

- Full-Year Simulations based on ETH 2050 Scenario (Base Case)

Figure description
- x-axis: One Summer Week (Hours 4000-4200)
- y-axis: Power In-feed (positive) / Outfeed (negative)
Assessment of Flexibility – Curtailed Renewable Energy in Europe

Modeling and Simulation of European Power System using Power Nodes

- **Power System** – 29 countries x up to 8 different aggregated Power Node types (load, wind, PV, hydro storage, fast/slow generation, CSP, DSP)
  → up to 232 Power Node units

- **Full-Year Simulations** with high temporal resolution (= 8'760 hourly steps)

- **Grid Topology** – 29 Node energy transfer model (using real Net Transfer Capacities)
Assessment of Flexibility – Curtailed Renewable Energy in Europe

There will soon be limits to RES integration without

- Hardware-based Adaptation (transmission and/or storage capacities) and
- Control-based Adaptation (DSM, DLR, other smart grid measures)

Performance Benchmark (central dispatch optimisation, no grid bottlenecks within countries, perfect prediction of wind/PV/load time-series, RES integration has priority)
Weekly NTC loading of the Swiss power system (Year 2010)

<table>
<thead>
<tr>
<th>FROM</th>
<th>TO</th>
<th>MW</th>
<th>MW</th>
</tr>
</thead>
<tbody>
<tr>
<td>CH</td>
<td>AT</td>
<td>-505</td>
<td>1100</td>
</tr>
<tr>
<td>CH</td>
<td>DE</td>
<td>-1780</td>
<td>3800</td>
</tr>
<tr>
<td>CH</td>
<td>FR</td>
<td>-3100</td>
<td>1700</td>
</tr>
<tr>
<td>CH</td>
<td>IT</td>
<td>-1625</td>
<td>3850</td>
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Weekly NTC loading of the Swiss power system with (Year 2050 with 50% RES)

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100% = fully loaded NTC, on a weekly basis
0% = no loading, on a weekly basis

ENTSO-E NTC 2010
First week of August
CH → IT (3850 MW)
- Low-RES (2010) ~100%
- High-RES (2050) ~50%
- Energy export (GWh/week) 647 324

Change of Load Flow Patterns around Switzerland

Master Thesis of Farid Comaty

Energy export (GWh/week)
Change of Load Flow Patterns in European Power System

Master Thesis of Farid Comaty

Year 2010

North to South

Year 2010 (50% RES)
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RES integration challenges are manyfold but – in principal – manageable.

Also other challenges (power markets, consumption growth, …).

Accurate modeling, simulation and analysis tools necessary for studying power systems and derive adaptation strategies from such decision support tools.

- **Hard Paths** – Solve problems simply by oversizing everything.
  (= oversized, expensive, inefficiently operated power system)

- **Soft Paths** – Solve problems via more control & optimal operation.
  (= right sized, less expensive, efficiently operated power system)

**Trade-Off** Computation is cheap (and getting cheaper), physical grid investments are expensive.

**Some References on Power Nodes**
- Ulbig and Andersson, IEEE PES General Meeting 2012.
ADAPTING ELECTRICITY GRIDS
Innovative Software for Power Systems in Transition

Dr. Stephan Koch, Dipl.-Ing. Andreas Ulbig, Dr. Francesco Ferrucci

- Conservative design, passive components
- Relatively straight-forward to plan and calculate
- No sophisticated operation strategies

Large $$ saving potential (if designed properly)

- Many degrees of freedom
- Optimal choice and concrete solution design is highly case-dependent
- Complex planning procedure, simulation studies necessary
- Implementation ultimately requires interaction with the real system

Novel Challenges in Distribution Grids

SmartGrid Solutions
- Temporary Renewable Curtailments
- Power Factor & Reactive Power Control
- Demand Response
- Distributed Storage

Which option to take? How to implement it?

Adaptricity Simulation Tools
- Predictive Dispatch Toolbox
- Grid Planning Toolbox

Adaptricity Field Software
- Predictive Dispatch Toolbox
Questions or Comments?

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