Course overview

- **Session 1:**
  - Introduction, variable generation, flexibility, netload
  - Excursus: Flexible Generation from coal?
    - *Exercise: Net load analysis (after coffee in different room)*

- **Session 2:**
  - System impacts and adapting operations
    - *Exercise: Reserve requirements and VRE forecasts*

- **Session 3:**
  - Economics of grid integration, system transformation
    - *Exercise: The value of variable generation*
Session agenda

**Session 1:**
Introduction, variable generation, flexibility, netload

1. Identifying relevant questions and issues
2. Grid based power systems: generation, transmission, distribution, loads
3. Relevance of balancing supply and demand across different time scales
4. 6 properties of variable renewable energy (VRE)
5. 4 sources of power system flexibility
   - Flexible Generation from coal?
6. Variable renewables as negative loads – the concept of net load

**Exercise 1:**

- Constructing net load for different shares of wind and PV
- Analysing net load ramps
- Average vs. Instantaneous penetration
Relevant questions and issues?
Some basics
Grid based power systems

- Grid based power systems are historically been organised into generation, transmission and distribution
- This is still main paradigm for most systems
Power demand varies by region, season and daytime.
Why is it challenging to balance supply and demand of electricity?
What are relevant time scales?
Properties of VRE
The 6 VRE properties that matter

- **Variable**
  - Maximum output varies depending on wind and sunlight

- **Uncertain**
  - No perfect forecast for wind and sunlight available

- **Non-synchronous technologies**
  - VRE connect to grid via power electronics, have little or no rotating mass

- **Location constrained**
  - Resource is not equally good in all locations and cannot be transported

- **Modularity**
  - Wide range of sizes and may be much smaller than other options

- **Low short-run cost**
  - Once built, VRE generate power almost for free
Variability: Examples of solar PV and wind
Uncertainty

- Uncertainty reduces dramatically with shorter horizon
- Real-time generation data key for short-term accuracy
- Forecasts generally more mature for wind than for PV
Excurse: Non-synchronous generation

Source: Characteristics of Wind Turbine Generators for Wind Power Plants IEEE PES Wind Plant Collecto System Design Working Group
Netload and flexibility
Netload = Load - VRE

Illustration of netload at different VRE shares

Note: Load data and wind data from Germany 10 to 16 November 2010, wind generation scaled, actual share 7.3%. Scaling may overestimate the impact of variability; combined effect of wind and solar may be lower, illustration only.
Four sources of flexibility ...

- Grid infrastructure
- Dispatchable generation
- Storage
- Demand side integration
What is flexibility?

Definition
- “Extent to which a power system can adjust the balance of electricity production and consumption in response to variability, expected or otherwise.”

Measurement of
- Flexibility supply
- Flexibility demand

Comparison of supply and demand
- Flexibility options may
  - Increase supply
  - Reduce demand


Operationalization of technical flexibility

- Extent of adjustment
  - Maximum change of supply/demand balance over a certain time horizon
  - Two scales [+/−MW] per time horizon

- But capability will depend on:
  - Past system state
  - Current system states
  - Future system state
  - VERY many dimensions

- This gives rise to complex effects that make mapping of a system on above scales challenging
Looking at the ideal power device

- Capable of:
  “Achieving and sustaining any consumption or generation level at arbitrarily small response times at no cost.”

- Relevant dimensions?
  - Possible levels: “Adjustability”
  - Max. duration of output: ”Durability”
  - Possible changes: “Ramping”
  - “Lead time” for change
  - “State dependency”

- Real power sources, loads & storage approximate ideal source on these dimensions
The 4 flexible resources

- **Flexible generation:**
  - Conventional plants and firm RE adjustable in wide range, very durable, more or less rampable, different lead time and state dependency (nuclear to OCGT)
  - Adjustability and durability of varRE limited by resource, but within these bounds they are very rampable, little response time, almost no state dependency

- **DSM**
  - Adjustable (consumption), varying durability, varying rampable, lead time, possibly high state dependency

- **Storage**
  - Perfect adjustability, determined durability ...

- **Interconnection**
  - Can reduce demand and increase supply along all dimensions
Focus on flexible generation

Or: can a coal plant really ramp?
**German hard coal plants carry most of ramping duty in Germany**
- Lignite and nuclear ramp as well, even nuclear at some times

**Ramping costs can be minimised at low cost; retrofits are possible** e.g. Flexible Coal: Evolution from Baseload to Peaking Plant (NREL, 2013)

*A sunny 1st May 2013 in Germany – actual production*

Source: Fraunhofer ISE
Experiences from coal in Denmark

Several Benson-pass cycles in one day! Components designed for 50 passes year. Redesign of component required due to fatigue. Assessment concluded no problem with life time in this case. In other cases the assessment may conclude that component must be replaced after X years.
It’s not the fuel – it’s the design and the operation

<table>
<thead>
<tr>
<th>Technology</th>
<th>Mini stable output (%)</th>
<th>Ramp rate (%/min)</th>
<th>Lead time, warm (h)</th>
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<tbody>
<tr>
<td>Reservoir hydro</td>
<td>5-6**</td>
<td>15-25</td>
<td>&lt; 0.1</td>
</tr>
<tr>
<td>Solid biomass</td>
<td>***</td>
<td>***</td>
<td>***</td>
</tr>
<tr>
<td>Biogas</td>
<td>***</td>
<td>***</td>
<td>***</td>
</tr>
<tr>
<td>Solar CSP/STE¹</td>
<td>20-30</td>
<td>4-8</td>
<td>1.4****</td>
</tr>
<tr>
<td>Geothermal</td>
<td>10-20</td>
<td>5-6</td>
<td>1-2</td>
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<td>Combustion engine bank CC</td>
<td>0</td>
<td>10-100</td>
<td>0.1-0.16</td>
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<td>40-50</td>
<td>0.8-6</td>
<td>2-4</td>
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<tr>
<td>Gas CCGT flexible</td>
<td>15-30*****</td>
<td>6-15</td>
<td>1-2</td>
</tr>
<tr>
<td>Gas OCGT</td>
<td>0-30</td>
<td>7-30</td>
<td>0.1-1</td>
</tr>
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<td>Steam turbine (gas/oil)</td>
<td>10-50</td>
<td>0.6-7</td>
<td>1.4</td>
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<tr>
<td>Coal inflexible</td>
<td>40-60</td>
<td>0.6-4</td>
<td>5-7</td>
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<tr>
<td>Coal flexible</td>
<td>20-40</td>
<td>4-8</td>
<td>2.5</td>
</tr>
<tr>
<td>Lignite</td>
<td>40-60</td>
<td>0.6-6</td>
<td>2.8</td>
</tr>
<tr>
<td>Nuclear inflexible</td>
<td>100******</td>
<td>0******</td>
<td>na******</td>
</tr>
<tr>
<td>Nuclear flexible</td>
<td>40-60******</td>
<td>0.3-5</td>
<td>na******</td>
</tr>
</tbody>
</table>

¹ CSP: Concentrated Solar Power; STE: Supercritical Steam Turbine
No problem at low shares, because ...

- Power systems already deal with a vast demand variability
  - Can use existing flexibility for VRE integration

*Exceptionally high variability in Brazil, 28 June 2010*
Exercise 1: Netload
Session agenda

■ Session 2:

System impacts and adapting operations

1. Overview of impact groups
2. Avoiding typical mistakes when beginning deployment
3. Focus on balancing
4. Focus on utilisation
5. Focus on grids
6. Specific challenges and opportunities of distributed, small-scale PV
7. Strategies for improving system operations

■ Exercise 2:

● Calculate impact of scheduling intervals on reserve requirements
● Assess benefit of using close to real-time forecast data
Different impact groups
Interaction is key

Properties of variable renewable energy (VRE)

- Variable
- Uncertain
- Non-synchronous
- Location constrained
- Modularity
- Low short-run cost

Flexibility of other power system components

- Grids
- Generation
- Storage
- Demand Side
# Properties of variable renewables and impact groups

- Systems are different – impacts will vary too
- But common groups of effects

<table>
<thead>
<tr>
<th>Seconds</th>
<th>Years</th>
<th>100km</th>
<th>1km</th>
</tr>
</thead>
<tbody>
<tr>
<td>Stability</td>
<td>Balancing</td>
<td>Profile / Utilisation</td>
<td>Location</td>
</tr>
</tbody>
</table>

- Low short run cost
- Non synchronous
- Uncertainty
- Variability
- Location constrained
- Modularity
- Stability
- Reserves
- Short term changes
- Asset utilisation
- Transmission grid
- Distribution grid
- Abundance
- Scarcity

- Properties of variable renewables
- Systems are different – impacts will vary too
- But common groups of effects
Issues investigated in integration studies

- 
- Generation Adequacy
- Grid Adequacy
- Planning
- CO\textsubscript{2} & Fuel Prices
- Tertiary Reserve (Unit Commitment & Replacement, Reserve & Network Control Reserve)
- 
- Secondary Reserve (AGC Regulation)
- 
- Primary Reserve (Governor Response) & Frequency Stability
- Electro-mechanical Stability (Rotor Angle Stability, Small Signal Stability, Sub-Synchronous Resonance)
- Congestion Management (Transmission Efficiency)
- Dispatch Balancing
- Security
- Transient Voltage Stability (LVRT)
- Fault Current Level & Protection
- Power Quality (Harmonics, Electromagnetic Transients)
- Power Quality (Harmonics, Electromagnetic Transients)
- Security
- 
- MOST RELEVANT SYSTEM STUDIES
- Australia (NEM)
- Iberia (REE & REN)
- Texas (ERCOT)
- Hydro Québec
- Ireland (All Island)
- Germany (DENA)
- New Zealand (Transpower)

Source: Dr Thomas Ackermann, Energynautics

Time-constant/Period time

years 1 month 1 day 1hr 1min 1s 100ms 10ms 1ms
Grid integration studies – best practice

- IEA Wind Implementing Agreement Task 25: Design and Operation of Power Systems with Large Amounts of Wind Power

Persistent impacts
Three typical mistakes to avoid when deployment begins

1. Excessive geographic, technical concentration
   - Key lessons: analysis based diversification of location and technology

2. Ill-adapted technical performance standards
   - Key lessons: focus on grid codes! (fault ride through, 50.2 Hertz); visibility and controllability

3. No or ineffective VRE production forecasts
   - Key lessons: use forecasts in unit commitment and dispatch of other generation
There is no single factor that would put a maximum technical limit on the long-term amount of variable generation.

However, more and more measures are needed to achieve high shares.

In the short term, many institutional and some technical issues can be a constraint.

Question rather is: How far can I go before it gets expensive? And what do I need to do for that?

*Apart from the speed of light
Main persistent challenge: Balancing

- Higher uncertainty
- Larger and more pronounced changes

Illustration of Residual power demand at different VRE shares

Note: Load data and wind data from Germany 10 to 16 November 2010, wind generation scaled, actual share 7.3%. Scaling may overestimate the impact of variability; combined effect of wind and solar may be lower, illustration only.
Hourly values in MW for different times of a day and days of a year in Spain and Portugal

Note: figures refer to year 2011
VRE impact – hourly differences (MW)

Hourly differences in MW for different times of a day and days of a year in Spain and Portugal

Note: figures refer to year 2011
Main persistent challenge: Utilisation

- Netload implies different utilisation for non-VRE system

Note: Load data and wind data from Germany 10 to 16 November 2010, wind generation scaled, actual share 7.3%. Scaling may overestimate the impact of variability; combined effect of wind and solar may be lower, illustration only.
Distributed PV and the grid 1/2

- Voltage rise common issue
- Smart inverters and transformers help

Voltage rise in a rural distribution system in Germany
Distributed PV and the grid 2/2

*Power flows across HV-MV transformer example from Bavaria, Germany*

Source: Bayernwerk, Fraunhofer IWES

- Reverse flows no big technical issue
- But too high concentration can imply costly retrofits

From Transmission to Distribution
From Distribution to Transmission
Wind in Texas – Operational issues while waiting on transmission

- Competitive Renewable Energy Zones (CREZ), Texas
- Wind built before completing all transmission lines
- Curtailment peaked at 17% in 2009
- Curtailment reduced to 1.6% in 2013 after implementing locational pricing and expanding the grid

Source: NREL

CREZ, Texas

Panhandle "A" (3.2 GW)
Panhandle "B" (2.4 GW)
Central West (1.1 GW)
Central (3 GW)
McCamey (1.9 GW)

345 kV double-circuit upgrades identified in CREZ transmission plan

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Excurse: Maximum penetration levels

Wind Generation, Ireland (as % of total demand)
Maximum non-synchronous penetration in Ireland

Adapting operations
Forecasting of VRE production key strategy for cost-effective operation

But operations need to make use of them:
- Adjust schedules to incorporate newest information
- Allows to extract all available flexibility

Accuracy of wind forecasts in Spain

Mean absolute error / average production

Forecast horizon (Hours before real-time)

Source: REE
Generation and transmission schedules

**Impact of scheduling interval on reserve requirements, illustration**

- **Short scheduling intervals (5min best practice)**
- **Adjust schedules up to real time (5min best practice)**
Co-operation with neighbours

- Germany has four balancing areas (historic reasons)
- Reserve sharing mechanism across four areas
- Reduced requirements despite rapid increase of VRE
System service definitions
Prepared for a variable future?

- Are your operating reserve and system service definitions VRE ready?
  - Example Ireland DS3 programme

**Voltage Services**

- Dynamic Reactive Power
- Steady-state Reactive Power
- Network Adequacy
- Grid 25
- Transient Voltage Response

**Frequency Services**

- Synchronous Inertial Response
- Fast Frequency Response
- Fast Post-Fault Active Power Recovery
- Ramping Margin

**Source:** EirGrid
Exercise 2: Reserve requirements and VRE forecasts
Session 3:
System friendly VRE, economics of grid integration, system transformation

1. Options for system friendly VRE deployment
2. Market fundamentals: stable and dynamic power systems,
3. Merit-order effect and utilisation effect
4. System costs and system value of variable generation
5. Economic analysis of the four flexible resources
6. System transformation and total system costs

Exercise 3:
- Calculate total system costs in a system where VRE are just added
- Calculate total system costs in a system where VRE and other plants can be matched to each other
System friendly VRE
Economics of VRE integration
Transformation depends on context

Stable Power Systems
• Sluggish demand growth
• Little general investment needed short-term

Example: Europe

Dynamic Power Systems
• Dynamic demand growth
• Large general investment needed short-term

Example: Emerging economies

* Compound annual average growth rate 2012-20, slow <2%, dynamic ≥2%; region average used where country data unavailable

This map is without prejudice to the status of or sovereignty over any territory, to the delimitation of international frontiers and boundaries and to the name of any territory, city or area.
Main market impacts in stable systems

- Reduced market *prices* (merit order effect)
- Reduced operating *hours* (utilisation effect)
- Displacement effect mainly due to
  - low short-run cost of VRE and
  - reinforced by support policies
  - influenced by variability, in particular PV
- Economic impact on gas generation result of several factors
The ‘merit order effect’
Main persistent challenge: Utilisation

- Netload implies different utilisation for non-VRE system

Note: Load data and wind data from Germany 10 to 16 November 2010, wind generation scaled, actual share 7.3%. Scaling may overestimate the impact of variability; combined effect of wind and solar may be lower, illustration only.
Utilisation: short term impact

Displacement of units with highest operating costs
Re-adaptation leads to displacement of technologies that are costly at low utilisation rates.
At growing shares of variable generation, cost savings in the residual system tend to slow

(Most) relevant economic effect, exact numbers system specific

Not captures by standard ‘back-up costs’
Examples of calculating balancing costs

- Modelled balancing costs are usually in the order of a few USD/MWh, highly system dependent, typically rise with VRE share
- Empirical data from German market: approx. 3 EUR/MWh to balance the FIT-portfolio
Investment in additional flexibility

Four sources of flexibility ...

- Grid infrastructure
- Dispatchable generation
- Storage
- Demand side integration
Interconnection can offer low-cost flexibility
Flexibility options – Electricity Storage

Where do you get inexpensive flexibility?

- Storage shows relatively high LCOF compared to other options
- But not only costs count – also the value matters
Flexibility options – DSI

Where do you get inexpensive flexibility?

- DSI potentially very favourable benefit/cost ratio
- Moving demand to when wind blows and sun shines increases firm capacity credit of variable sources
- But what is the real potential?
Flexibility options – Generation
Where do you get inexpensive flexibility?
**Benefit/cost of flexibility options**

**North West Europe - DSI**

- Overall system savings of 2.0 bln $/year
- DSI costs of 0.9 bln $/year

**Benefit/cost ratio: 2.2**

Note: graph represents the differences between DSI scenario (DSI 8% of overall demand) and baseline scenario.

DSI assumed to be 8% of annual power demand:
- 71% made of heat and other schedulable demand (110 TWh)
- 29% EV demand (44 TWh)

CO₂ price USD 30 per tonne
Coal price USD 2.7/Mmbtu
Gas price USD 8/Mmbtu
DSI has large benefits at comparably low costs

Interconnection allows a more efficient use of distributed flexibility options and generates synergies with storage and DSI

Cost effectiveness of hydro plant retrofit depend on project specific measures and associated investment needs

Notes:
1) CAPEX assumed for selected flexibility options: interconnection 1,300$/MW/km onshore and 2,600$/MW/km offshore, pumped hydro storage 1,170$/kW, reservoir hydro 750 $/kW - 1,300$/kW (repowering of existing reservoir hydro increasing available capacity). Cost of DSI is assumed equal to 4.7 $/MWh of overall power demand (adjustment of NEWSIS results)
2) Fuel prices and CAPEX ($/kW) for VRE and flexibility options are assumed constant across all scenarios

Source: IEA/PÖYRY
Investments in system flexibility – Need for a suite of solutions

- No single resource does it all!
- Example:
  - Abundance
    - Flexible generation ✗ ✗
    - DSI ✓
    - Storage ✓
    - Curtailment ✓
  - Scarcity
    - Flexible generation ✓ ✓
    - DSI ✗
    - Storage ✓
    - Curtailment ✗ ✗

Solar and wind can be abundant ...

... or scarce.

Data: Germany 2011, 3x actual wind and solar PV capacity
System transformation and total system costs
Integration vs. transformation

- Classical view: VRE are integrated into the rest
  - Integration costs: balancing, adequacy, grid

- More accurate view: entire system is re-optimised
  - Total system costs

Integration is actually about transformation

Remaining system

VRE

Power system

- Generation
- Grids
- Storage
- Demand Side Integration
Three pillars of system transformation

1. Let wind and solar play their part
2. Make better use of what you have
3. Take a system wide strategic approach to investments!

- Technology spread
- Geographic spread
- Design of power plants
- System friendly VRE

Investments

Operations
Cost-effective integration means transformation of power system

- Large shares of VRE can be integrated cost-effectively
- Significant optimization on both fixed and variable costs
Exercise 3: Effects of VRE on total system costs
Add-on: integration costs
Decomposition always challenging:
- Balancing, adequacy, grids
- Uncertainty, profile, location
- Unclear that all effects are covered with these practices; categories not independent

Calculation requires reference technology:
- Common benchmark for all technologies can skew the calculation (flat block benchmark) or miss important adaptation options (load correlated benchmark)
- Portfolio of technologies (not just generation) needed to minimise total system costs.
Problems with calculating integration costs

 Decomposition always challenging:

- Balancing, adequacy, grids
- Uncertainty, profile, location

  ➔ Unclear that all effects are covered with these practices; categories not independent

 Calculation requires reference technology:

- Common benchmark for all technologies can skew the calculation (flat block benchmark) or miss important adaptation options (load correlated benchmark)

  ➔ Portfolio of technologies (not just generation) needed to minimise total system costs.
Alternative: System value

- Benchmark VRE against net savings in residual power system – more useful than trying to calculate integration costs

- System value depends on transformation of the system