Features of intermittent electricity supply
F. Wagner, Max-Planck-Institut für Plasmaphysik, Greifswald

Topic: Transformation of energy system; fossil → RE

Now: PE(chemical) \{ Mechanical energy (transport) \\
Electricity \\
Heat \}

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Electricity \\
Heat \}

We may not forget:

fossil fuel technology allowed mankind to grow to > 7 bn people on earth

We employ 45 slaves to lead the life of our joice (45 = 5500W/120W)

Our economy provides ~ 500 bn€/a for social programs
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Future: RE \{ \\
Hydro: limited \\
Bio-mass: limited \\
Geo-thermal: limited to regions \\
Wind \\
Solar \} scalable, low energy density, intermittent
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scalable, low energy density, intermittent

Chemical energy (storage)
Heat (heat pump)
Electricity → transport
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Topic: Transformation of energy system; fossil → RE

Now: PE(chemical) 

Future: RE

The essence of the „Energiewende“

Mechanical energy (transport)
Electricity
Heat

Hydro: limited
Bio-mass: limited
Geothermal: limited to regions
Wind
Solar
scalable, low energy density, intermittent

Chemical energy (storage)
Heat (heat pump)
Electricity → transport
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PE (electrical) \{ Chemical energy (storage) \\
Heat (heat pump) \\
Electricity → transport \}
Goal:

Use the present German situation to characterize electricity supply by wind and photo voltaic (PV) power

Why Germany? largest electricity consumer in the middle of the EU grid most advanced in the use of RE
Electricity demand during the day

Definition: load = demand

Tue 31.1.2012

Peak load

Base load

Power (MW)

Time (h)
Electricity demand during the day

Definition: load = demand

Power (MW) vs. time (h)

Peak load and base load for Tue 31.1.2012

Important: Demand has to be met by supply for every moment
Electricity demand during the day

Definition: load = demand

**Peak load**

**Base load**

**Tue 31.1.2012**

- **6:00**
- **12:00**
- **18:00**

**Definition: load = demand**

**Power (MW)**

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</tr>
</tbody>
</table>
Electricity demand during the day

Definition: load = demand

Tue 31.1.2012

Peak load

Base load

65 GW x 24 h x 365 days = 600 TWh
Electricity demand during the week

![Graph showing electricity demand over a week with power (MW) on the y-axis and time (days) on the x-axis. Peaks are observed on Monday and Friday, with dips on Wednesday and Thursday.](image-url)
Electricity demand during the year 2012

- During the week
- At the weekend
- Christmas period
Growth of installed wind and PV power in Germany

- Onshore wind: 32.5 GW
- PV: 36 GW
Energy carriers for electricity

2012

- Coal
- Lignite
- Oil
- Gas
- Nuclear
- Hydro
- Wind
- PV
- Biomass
- Rest
The task of the future…
Situation 2012

\[ W_{\text{off}} = 160 \text{ MW} \]

in the diagram: multiplied by 200
Why the different profiles of on- and offshore wind?
Comparison load – installed RE in Germany
Comparison load – installed RE in Germany

PV and Wind cover a large part of the demand.

Surplus incurs

Max. load: 83 GW

Power:

Wind: 32.5 GW; 39 %
PV: 36 GW; 43 %

Energy:

Wind: 50.7 TWh; 8.1 %
PV: 26.4 TWh; 4.2 %

RE demand large power installations
Scaling to 100%

Scale 2012 data to higher installed powers and analyse

**Assumptions:**
electricity demand will not change  
(electric cars, saving measures, air conditioning)

Hydroelectricity and electricity from waste will not change

Biomass will be used for transportation not for electricity production

Target: 630 TWh produced – 595 used – 537 net – hydro: 21, waste: 5 TWh

**Target: reduced load:** 500 TWh

100% case: wind and PV produce 500 TWh
Duration curve: load

- Peak: 2000 h
- Middle: 6000 h
- Base load

Power (MW)

Time (months)

2012
Duration curve

1: reduced load
2: back-up
3: Woff x 200
4: PV
5: Won

grey: fossil power
red: nuclear power
Duration curve

1: reduced load
2: back-up
3: Woff x 200
4: PV
5: Won

1: reduced load
2: back-up
3: Woff x 200
4: PV
5: Won

one month
half year

Power (MW)

Time (months)
The problem with RE

Load and RE demand curve do not fit

Production of surplus at a high power level
Scaling to 100% supply by RE

- 100%-case: back-up energy = surplus energy
- Even for the 100% case a thermal back-up system is needed as long as storage is not available
How to mix wind and PV power?

Wind is erratic and strong in winter
PV is periodic, strong in summer and aligned to the maximal demand

→ there is an optimal mix between wind and PV
Minimisation of back-up energy

Residual load necessary when RE do not match the demand

12.-19.2.2012

5.-12.8.2012
Optimal mix between wind and PV

Optimal mix: PV energy / residual load: ~20%
Optimal mix between wind and PV

Optimal mix: PV energy / residual load: ~ 20 %
Splitting of on- and offshore wind: Won = 2/3 W; Woff = 1/3 W
Advantage of the optimal mix

EPS-SIF energy workshop, Varanna 2014

- Graph showing the power (MW) over time (months) for different scenarios.
- "Last 100% opt mix" and "100% opt mix" compared.
- "Surplus" and "back-up" indicated.

Graphs display power levels and time in months.
Scaling to 100% supply by RE

Onshore wind

Offshore wind

PV

back-up

power (MW)

2012

reduced load

100% opt. mix

months

months

months

months
The 100% case realised in Denmark: 21.12. 2013
The 100% case realised in Denmark: 21.12. 2013
The 100% case realised in Denmark: 21.12. 2013

For the 100% case: surplus energy = back-up energy
The 100% case of Denmark

The 100% case realised in Denmark: 21.12. 2013

Dk situation

ref. P.-F. Bach

<table>
<thead>
<tr>
<th>Date</th>
<th>MWh</th>
</tr>
</thead>
<tbody>
<tr>
<td>21 December 2013</td>
<td>94.118</td>
</tr>
<tr>
<td>Gross consumption</td>
<td>48.975</td>
</tr>
<tr>
<td>Net export</td>
<td>96.161</td>
</tr>
<tr>
<td>Thermal production</td>
<td>46.933</td>
</tr>
</tbody>
</table>
Back-up system

Operation of the Rostock coal power station
Anti-correlation of thermal power and wind power (50Hertz)

3. and 4. week in Okt. 2010

wind level where the power station switches off
The power of the back-up system remains high

It has to meet the full dynamic range from 0 to nearly peak load

The power gradients increase strongly
The surplus problem

**PST (Phase Shift Transformer)** recommended and planned in ENTSO-E transmission grids

- **BE**
  - Rz. Zandvliet
  - Un: 400 kV
  - Sn: 1400 MVA
- **BE**
  - Rz. Van Eyck
  - Un: 400 kV
  - Sn: 1400 MVA
- **IT**
  - Rz. Ronsebone
  - Un: 400 kV
  - Sn: 1630 MVA
- **FR**
  - Rz. Praz
  - Un: 400 kV
  - Sn: 1200 MVA
- **FR**
  - Rz. Pragneres
  - Un: 220 kV
  - Sn: 280 MVA
- **IT**
  - Rz. Camparosso
  - Un: 220 kV
  - Sn: 450 MVA
- **AT**
  - Rz. Ernststehen
  - Un: 220 kV
  - Sn: 600 MVA
- **AT**
  - Rz. Taurern
  - Un: 220 kV
  - Sn: 600 MVA
- **AT**
  - Rz. Lienz
  - Un: 220 kV
  - Sn: 330 MVA
- **AT**
  - Rz. Ternitz
  - Un: 220 kV
  - Sn: 600 MVA
- **IT**
  - Rz. Foggia
  - Un: 400 kV
  - Sn: 1800 MVA
- **IT**
  - Rz. Padriciano
  - Un: 220 kV
  - Sn: 370 MVA
- **PL**
  - Rz. Krajnik
  - Un: 400 kV
  - Sn: 2x1700 MVA
- **PL**
  - Rz. Gubin
  - Un: 400 kV
  - Sn: 2x1700 MVA
- **PL**
  - Rz. Mikułowa
  - Un: 400 kV
  - Sn: 2x1700 MVA
- **CZ**
  - Rz. Hradec
  - Un: 400 kV
  - Sn: 2x1700 MVA
- **HR**
  - Rz. Ženiževinec
  - Un: 400/220 kV
  - Sn: 400 MVA
- **SI**
  - Rz. Divača
  - Un: 400 kV
  - Sn: 1200 MVA

Region: **ENTSO-E soustava**
- Region kortečky
- Region blaho
- Region uměl
- Region vnitřní

Synchronní zóny
- **ENTSO-E soustava**
- Region kortečky
- Region blaho
- Region uměl
- Region vnitřní

Ready for implementation:
- **PST**
  - Un: 400 kV
  - Sn: 2x1250 MVA

Planned:
- **PST**
  - Un: 400 kV
  - Sn: 2x1250 MVA

Recommended:
- **PST**
  - Un: 400 kV
  - Sn: 2x1250 MVA
The surplus problem

**PST (Phase Shift Transformer)** recommended and planned in ENTSO-E transmission grids

A high degree of control of cross-border flow is necessary.
Specification of the 100%, optimal mix case

Germany

$P_{\text{Won}} = 176 \text{ GW} ; P_{\text{Woff}} = 33 \text{ GW}; P_{\text{PV}} = 97 \text{ GW} \rightarrow P_{\text{RE}}^{\text{installed}} = 306 \text{ GW}$

$P_{\text{load}} = 83 \text{ GW} ; P_{\text{back-up}} = 73 \text{ GW}$

$W_{\text{Won}} = 271 \text{ TWh} ; W_{\text{Woff}} = 135 \text{ TWh} ; W_{\text{PV}} = 94 \text{ TWh} ; W_{\text{RE}} = 500 \text{ TWh}$

$W_{\text{back-up}} = 131 \text{ TWh} ; W_{\text{surplus}} = 131 \text{ TWh}$

12% reduction of back-up power

The total installed power (306 + 73 GW) compares with the load of the EU: ~ 400 GW

The surplus corresponds to the annual demand of Poland
2012 compared to „100%, opt. mix. - case“

The „Energiewende“ is still in its infancy
Storage

100%, optimal mix case

black: Last
red: back-up
blue, negative: surplus

Jan / Feb 2012

100%, optimal mix case

black: Last
red: back-up
blue, negative: surplus

<table>
<thead>
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<th>h</th>
<th>66</th>
<th>90</th>
<th>117</th>
<th>67</th>
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100%, optimal mix case

black: Last
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blue, negative: surplus
100%, optimal mix case

- black: Last
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Storage

100%, optimal mix case

black: Last
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storage level (TWh)

Storage

100%, optimal mix case

black: Last
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blue, negative: surplus

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Storage capacity in the order of 10 TWh
Present pumped water storage situation: ~ 50 GWh, ~ 7 GW

To replace the back-up system, the 100%, optimal mix case demands a storage of 33 TWh = 650 x presently installed capacity of Germany

A target storage value could be: 5 TWh.
Only chemical storage possible; technology not available at large scales

Such a system would consist of:

\[ P_{\text{RE}} \text{ not changed} (P_{\text{Won}} = 176 \text{ GW}; P_{\text{Woff}} = 33 \text{ GW}; P_{\text{PV}} = 97 \text{ GW}) \]

\[ P_{\text{storage}} = -123 (+73) \text{ GW}; \quad P_{\text{back-up}} = 71 \text{ GW} (-15\%) \text{ for } 42 \text{ TWh} (131 \text{ TWh}) \]

**Capacity factors of system (%):**

<table>
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<tr>
<th></th>
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**Problem:** no component operates economically
Demand-side management

Principle: shift economic activities into low-cost periods

Average of daily variation of load, back-up and surplus
Demand-side management

**Principle:** shift economic activities into low-cost periods

Average of daily variation of load, back-up and surplus

**Low price period is during the day, not the night!**
Demand-side management

Comparison winter - summer

- **Winter:**
  - Time: 10:00 – 16:00
  - Power: 10^4 – 10^5 MW
  - Time: 23:00 – 6:00

- **Summer:**
  - Time: 9:30 – 18:00
  - Power: 9:30 – 18:00
  - Time: 10^4 – 10^5 MW
Demand-side management

Use of daily storage

Storage capacity: 0.3 TWh

Reduction of back-up system:
131 → 103 TWh
Demand-side management

Situation during weekend

![Graph showing power (MW) versus time (h) from 6:00 to 17:30]
Demand-side management

Situation during weekend

Full integration of weekends:

Additional use of RE: 7.9 TWh

Peak-load: 83 → 63 MW

Reduction of back-up system:
131 → 123 TWh

Integration of weekends has about 1/3 the effect of a storage which is larger than the present one by a factor of 6.
CO$_2$ reduction by RE

Optimal mix conditions

- Fossil fuel mix
- Natural gas
CO\textsubscript{2} reduction by RE

Optimal mix conditions

\[ \eta_{el} \text{ (kgCO}_2\text{ /kWh)} \]

- fossil fuel mix
- natural gas

\[ \text{RE fraction (\%)} \]

\[ \text{storage fraction (\%)} \]

5 TWh
CO$_2$ reduction by RE

Optimal mix conditions

Storage is hardly motivated by CO$_2$-saving
It is difficult to meet the spez. CO₂ production of hydro- and nuclear with RE
The benefits of an EU-wide grid

Wind data: Spain, France, Ireland, UK, Belgium, Germany, Czech Rep., Denmark
PV data: Spain, France, Germany, Czech Rep.

Duration curves
  load
  onshore wind
  PV

Dashed curves: Germany
Solid curves: averages
The benefits of an EU-wide grid

Wind data: Spain, France, Ireland, UK, Belgium, Germany, Czech Rep., Denmark
PV data: Spain, France, Germany, Czech Rep.

Duration curves
- load
- onshore wind
- PV

Dashed curves: Germany
Solid curves: averages

Only wind shows a distinct averaging effect
The benefits of an EU-wide grid

Wind data: Spain, France, Ireland, UK, Belgium, Germany, Czech Rep., Denmark
PV data: Spain, France, Germany, Czech Rep.

<table>
<thead>
<tr>
<th>Pair of countries</th>
<th>R</th>
</tr>
</thead>
<tbody>
<tr>
<td>Germany-Czech Rep.</td>
<td>0.53</td>
</tr>
<tr>
<td>Germany-Denmark</td>
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<tr>
<td>Germany-Belgium</td>
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<td>Germany-France</td>
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<td>Germany-UK</td>
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<td>Germany-Ireland</td>
<td>0.19</td>
</tr>
<tr>
<td>Germany-Spain</td>
<td>0.05</td>
</tr>
</tbody>
</table>

The importance of Spain: wind-fields are decorrelated
Surplus ratio:
\[ \text{total surplus/matched surplus} - 1 \]

When a country produces surplus also the neighbours produce it.
The benefits of an EU-wide grid
The benefits of an EU-wide grid

**Benefit for** back-up system (total load: 1761 TWh)

- Countries individually: 446 TWh
- Countries jointly: 323 TWh
- Saving in thermal back-up power: 100% case, national: - 16% in the average
- 100% case, EU-RE-field: - 28%

But: the interconnection capacity has to be increased to typically 60% of the load
The role of PV in an EU-wide mix

Solar contributions are basically irrelevant in an EU-wide mix
Wind and PV electricity is possible in large scales if the necessary space is allocated

Large power to be installed – comparable to the load of Europe → **high costs**

40 % of wind and PV might be reasonable

Back-up system required in all scenarios: **little saving in thermal power**

Components operation not economic → today: **no new gas power stations**

Unfavorable operation of all technical systems → **increased costs and CO₂**

High surplus power peaks and energies: **what to do with ?**

  - Suppress → further degradation of economic operation
  - Use for power-to-gas: high prices of secondary electricity
  - Use for heating: winter production: 76 TWh (private heating: 550 TWh)
  - Use for cooling: summer production: 55 TWh (cooling needs: 20 TWh)
  - Store for electric cars: 100 TWh required
Conclusions 2

Storage (for surplus power):

- Large-scale technology, not yet available
- Operation not economic
- Difficult to motivate from the CO₂ saving point of view

Electricity supply cannot be organised under present market rules → capacity market

CO₂ reduction by RE: not to the levels as already achieved by others in EU

No favorable conditions for demand-side management:

- Day-time activities will intensify: maybe, new markets will develop
- Best options: use of weekends
- Storage by car batteries: surplus during the day not the night

Supra-national supply improves situation: will it ever be realised?
The exclusive use of RE has limitations and leads to shortcomings.

Therefore, the most obvious question will be whether and how an electricity system based on intermittent sources can be improved or supplemented.

This will be a question classically posed to research and engineering because these disciplines have found the ways in the past to liberate mankind from the imponderabilities and perils of nature.