Integration of variable electricity sources
F. Wagner, Max-Planck-Institut für Plasmaphysik, Greifswald/Garching

Out of environmental reasons:
Transformation of the energy system

Today: PE: chemical
  Mechanical energy (transport)
  Electricity
  Heat

Future: PE: electrical
  Chemical energy (storage)
  Heat (heat pump)
  Electricity → transport
Energy production by variable sources
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Today: PE: chemical
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- Electricity → transport
Electricity consumption

**Germany:**

electricity production: 648 TWh (2016)
- internal needs of power stations
- transformation, transportation losses
- export
→ net electricity consumption: 540 TWh

per-capita: 6.6 MWh
corresponds to: 752 W
Electricity consumption

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Specifics of electricity consumption

Load variation during Tue 31.1.2012

Important:
Supply has to meet demand at every moment

It is not sufficient to talk on integral values of energy only

Consumption is very variable e.g. cooking needed: 3800 W for 2 hours average in the day: 320 W

Time-resolved analysis is necessary
Specifics of electricity consumption

Load variation during the week

Seasonal variation

- During the week
- At the weekend
- Christmas period
Descriptive parameters

Peak value: 83 GW
average value: 57 GW
minimum value: 33 GW

57 GW $\times$ 8760 h = 500 TWh
83 GW $\times$ 8760 h = 727 TWh

System use: 69%
= capacity factor

Full-load hours flh
= 8760 $\times$ $<P>/P_{\text{max}}$ = 6000 h
Annual duration curves
Electricity production - today

Electricity mix 2016

- Lignite: 150 TWh
- Coal: 110 TWh
- Nuclear: 85 TWh
- Gas: 79 TWh
- Others: 34 TWh
- Wind: 80 TWh
- Biomass: 52 TWh
- PV: 38 TWh
- Hydro: 22 TWh

Renewable energies: 220 TWh
The transition to renewable energies only

2012: 520 TWh endenergy

100%-case

Hydro + Biomass are limited

Only onshore, offshore wind and photovoltaik power (PV) are scalable

onshore

offshore

PV

wind

hydro

biomass

waste

nuclear

oil

gas

coal

lignite
The characteristics of wind and PV power

- **Low power density**
  - Wind: 2-3 W/m²
  - PV: 5 W/m²

- **Large areas needed**

- **Large material investments**

For comparison:
- Germany total energy density: 1.1 W/m²
- Munich only electricity: 2.5 W/m²
Intermittency of power production

Data of 2015

Onshore wind

PV
Intermittency of power production

[Graphs showing power production over time (month)]
The consequences of intermittency

- Installed onshore wind power: 41.2 GW
  - Average power: 8.4 GW
  - Installed power: 39.3 GW

- Offshore: 3300 h

\[ f_{th} = 1786 \text{ h} \]

\[ 892 \text{ h} \]
The consequences of intermittency

Intermittent renewable power iRES is not always available

→ **backup** system necessary

High power installation necessary to produce required energy

→ **surplus** production

Wind and PV produce 500 TWh
The basic problem of iRES

Annual Duration Curve ADC

Load and production curve do not fit

To gain energy: large capacities high power levels
The basic problem of iRES

annual duration curves for 100% case

![Graph showing annual duration curves for iRES](image)

- $p_{\text{max}}$
- $p_{\text{min}}$
- $<p>_{\text{iRES}}$
- $<p>_{\text{load}}$
The basic problem of iRES

annual duration curves for 100% case
Transition in energy technology

Endenergy: 520 TWh

Analysis method:
- scale wind and PV to 100%
- 100%-case = 500 TWh

Assumptions
- hydro limited to 20 TWh
- no nuclear power
- no bio-gas (at present: 50TWh)
- no export, import
- wind and PV ratio: optimal mix

1. analysis step: **no losses**
Public data source

From the four German grid operators
http://www.tennetso.de/
http://www.50hertz-transmission.net/
http://www.amprion.de/
http://transnet-bw.de/

From the EU organisation ENTSOE
http://www.entsoe.net/
Optimal mix between wind and PV

\[ E_{\text{PV}} \sim 20\%; \quad E_{\text{wind}} \sim 80\% \]

\[ P_{\text{PV}} = \frac{E_{\text{PV}}}{flh_{\text{PV}}}; \quad P_{\text{wind}} = \frac{E_{\text{wind}}}{flh_{\text{wind}}} \rightarrow P_{\text{PV}} \sim 30\% \]
Analysis Examples

Germany as role-model for the “Energiewende”

![Graph showing installed power vs energy (TWh)]
Analysis Examples

Germany as role-model for the "Energiewende"

Because of intermittency:
- high installed power
  2016: ~ 28000 windmills
- Installed power level never reached
- strong variation from year to year
- Low capacity factor:
  cf ~ 15%
- Back-up system required

- **Installed power**
  - $P_{\text{max}}$
  - $P_{\text{min}}$
  - $\langle P \rangle$

- **Power (MW)**
  - $1 \times 10^5$
  - $8 \times 10^4$
  - $6 \times 10^4$
  - $4 \times 10^4$
  - $2 \times 10^4$
  - $1 \times 10^4$
  - $0$

- **Energy (TWh)**
  - 150
  - 100
  - 50
  - 0
1. example: How much power has to be installed?

100%, optimal mix case: 
av. value 2010-2015: 
**335 GW** (= 4kW/person; 
4x peak load) 
\[ P_{\text{won}} = 174 \text{GW} \] 
\[ P_{\text{woff}} = 43 \text{GW} \] 
\[ P_{\text{PV}} = 118 \text{GW} \]

17% energy variation from year to year

73 GW to produce 132 TWh the needed back-up power is larger than the fossil power of today

Build-up of tremendous overcapacity
No economic use of back-up investment
Surplus and back-up production

100% case:
surplus = back-up energy
~ 25% of total generation
~ 125 TWh
2. Example: Scenarios for using surplus

100%, optimal mix case

**Quantitatively:**

average daily need: 1.36 TWh

<table>
<thead>
<tr>
<th>Date</th>
<th>Surplus</th>
<th>Back-up</th>
</tr>
</thead>
<tbody>
<tr>
<td>2.4.2012</td>
<td>0.47 TWh</td>
<td>0.37 TWh</td>
</tr>
<tr>
<td>15.11.2012</td>
<td>0 TWh</td>
<td>1.47 TWh</td>
</tr>
<tr>
<td>31.12.2012</td>
<td>2.33 TWh</td>
<td>0 TWh</td>
</tr>
</tbody>
</table>
Problems of Demand-side management

surplus power for the 100%, optimal mix case for 21 days in April 2012

**Strong variation of surplus power**

44 TWh out of 131 TWh could be transferred from surplus to demand periods

No surplus for 134 days
3. Example: Fluctuation level

Power jumps within 15 min

$$\Delta P_i = P_{i+1} - P_i$$
3. Example: Fluctuation level

Power jumps within 15 min

\[ \Delta P_i = P_{i+1} - P_i \]

100%, optimal mix case
4. Example: Seasonal storage

100%, optimal mix case

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

<table>
<thead>
<tr>
<th>h</th>
<th>66</th>
<th>90</th>
<th>117</th>
<th>67</th>
<th>27</th>
<th>71</th>
<th>70</th>
<th>264</th>
</tr>
</thead>
<tbody>
<tr>
<td>TWh</td>
<td>3.7</td>
<td>-3.5</td>
<td>4.5</td>
<td>-2.5</td>
<td>0.5</td>
<td>-2.4</td>
<td>0.8</td>
<td>-10.4</td>
</tr>
</tbody>
</table>

Example: Seasonal storage 100%, optimal mix case black: load red: back-up blue, negative: surplus
Seasonal storage

100%, optimal mix case

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

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storage level (TWh)

Variation from year to year

- Ideal storage
  - No losses

Periodic boundary conditions
- Maximum = capacity
- Once empty during the year

Graph showing data from 2010 to 2015 with filling levels in TWh over time (months).
The effect of efficiencies

Assume: chemical storage and power-to-gas-to-power

1. step: electrolysis with surplus: $\eta \sim 0.65-0.7$
2. step: electricity from $\mathrm{H}_2$: $\eta \sim 0.5$ (fuel cell)

Alternatively
2. step: $\mathrm{H}_2$ to $\mathrm{CH}_4$: $\eta \sim 0.65$
3. step: $\mathrm{CH}_4$ to electricity: $\eta \sim 0.5$

Total efficiencies: $\eta \sim 0.2 - 0.35 \rightarrow$ for 1 kWh output, 3 - 5 kWh input

From 131 TWh surplus, 25 - 45 TWh can be recovered
Transformation losses: power-to-gas

Seasonal storage loses character: short operational periods after bursts of surplus

2012, no losses (1)

electricity $\rightarrow$ H$_2$ (0.8)

electricity $\rightarrow$ H$_2$ $\rightarrow$ electricity (0.6)

electricity $\rightarrow$ H$_2$ $\rightarrow$ CH$_4$ $\rightarrow$ electricity (0.4)
5. Example: Conditions of a 100% electricity supply by RES

Main knobs: savings/efficiency + use of biomass
Minor knobs: decrease of population, import (dispatchable power), geo-th-power
6. Example: CO$_2$ emissions

![Graph showing CO$_2$ emissions and fraction of RES](image)

**Germany 2002-2015**

- **CO$_2$ emissions**
- **fraction of RES (%)**
- **electricity mix (%)**

- **fossil mix only**
- **exclusively gas**
7. Example: Benefits from an EU-wide RES field

<table>
<thead>
<tr>
<th>Country</th>
<th>Technology</th>
</tr>
</thead>
<tbody>
<tr>
<td>Germany</td>
<td>wind+PV</td>
</tr>
<tr>
<td>Denmark</td>
<td>wind</td>
</tr>
<tr>
<td>Belgium</td>
<td>wind</td>
</tr>
<tr>
<td>France</td>
<td>wind+PV</td>
</tr>
<tr>
<td>UK</td>
<td>wind</td>
</tr>
<tr>
<td>Ireland</td>
<td>wind</td>
</tr>
<tr>
<td>Spain</td>
<td>wind+PV</td>
</tr>
<tr>
<td>Czech Rep.</td>
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</tr>
<tr>
<td>Sweden</td>
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Distribution of wind field expressed as regression coefficient.
The benefit of working with an EU-wide RES field

- the back-up energy is reduced by 24%,
- the maximal back-up power by 9%,
- the maximal surplus power by 15%,
- the maximal grid power by 7%,
- the typical grid fluctuation level by 35%
- the maximal storage capacity by 28%
Useful surplus (from German point of view)

normalised surplus
and
„useful“ surplus

In case of surplus – also the neighbours produce it
Interconnector capacity
Conclusion

EU-wide consequences

Large RES power necessary for all countries
National RES use demands typically north-south grids
Cross-border exchange requires east-west grids
Exchange over large distances beneficial
Large interconnector capacities needed
Not all countries benefit from an EU-wide RES field
6. Example: Going beyond electricity

Energy production and needs of all energy sectors
Issues of full de-carbonisation

- Traffic
- Heat, water
- Process heat
- Electricity

Savings according to V. Quaschning

Installed power needed: ~ 1000 GW

Average power: 1300 TWh

Energy needed: 2400 TWh

Power (GW) vs. energy needed (TWh)
Overproduction of electricity

back-up and surplus production

Germany’s neighbours

![Graph showing energy and storage capacity](image)
Overproduction of electricity
- a good example for the need of time-resolved studies

Still periods where electricity demand cannot be met
Overproduction of electricity

- a good example for the need of time-resolved studies

Still periods where electricity demand cannot be met

Strong grid dynamics
Conclusions

Data on electricity production and consumptions are easily available.

They can be used in a simple and transparent form to analyse the energy transition using mostly intermittent sources.
Publications along this line

**Germany**
H. W. Sinn “BUFFERING VOLATILITY: A STUDY ON THE LIMITS OF GERMANY’S ENERGY REVOLUTION”, accepted for publication in European Economy Review.

**France**

**Italy**

**Czech Republic**

**Sweden**

**Spain**
R. Gómez-Calvet et al. “Present state and optimal development of the renewable energy generation mix in Spain” to be published in Renewable and Sustainable Energy Reviews

**EU**
Major Results

How much power has to be installed? Enough to serve Europe in good days

The remaining need for back-up power? 12% saving in power; 2 parallel systems are needed

The extent of surplus energy? Formally enough to serve Poland

Dimension of seasonal storage? For the 100% case: 660 x present capacity

The dynamics of the back-up system? From 0 up to the load; strong gradients

The conditions for DSM (demand-side management)? Cheap electricity prices during the day

The amount of CO₂ reduction? Not to the level of France, Sweden, Switzerland...

Conditions of a 100% supply by RES? Use of biogas (e.g. 40 TWh) and savings (down to 30%)

What could be a reasonable share by iRES? 40%
Thank you
Comparison of specific CO₂ emissions

Germany 2002-2015

fraction of RES (%)
GHG and CO$_2$ emissions from Germany

- Total GHG-emission
- CO$_2$-emission via electricity generation
- Extrapolation on basis of present decisions
- If coal instead of nuclear had been switched off
- If coal had been replaced by gas
Demand-side management

Integration of weekends into economic activities

- Additional use of iRES: 7.9 TWh
- Peak-load: 83 → 63 MW
- Reduction of back-up system: 131 → 123 TWh
Other uses of surplus energy

1. Production of H₂ for industrial purposes

2 MW → ~ 360 m³/h: 130 TWh (f_{RES}=1) → ~ 20 Mrd m³ H₂ ~ use in German industry

2. For heating

- a substantial share is possible
- for f_{RES}=1 not sufficient
- for f_{RES}=2 heat insulation needed
Surplus production today

Today:

The electricity export strongly increases and agrees **nominally** with the PV energy generated.
The use of biomass

Biomass =
Residual material, biogenic waste
Crops = raps (diesel), corn+cereal (biogas → electricity, 50 TWh), cereal+sugar beets (ethanol)
Wood: 19% (2015) of German wood harvest for energetic use (burned)

Involved areas:
agriculture total: 18 Mill ha
animal food: 10.2 Mill ha; food: 4.5 Mill ha; bioenergy: 2.1 Mill ha → PE of 270 TWh
forest: 10.7 Mill ha

Limiting factors:
Waste: about 2/3 is already used
All gen. 1 bioenergies (crops) have low (or no) GHG savings
Agriculture: 1/3 of animal food proteins imported as Soja beans. Would need 3 Mill ha
Forest: total use of wood: 120 Mill m³; national production ~ 55 Mill m³; Carbon content of forests critical
Signs of losing bio-diversity in Germany

Conclusion: Biomass is strongly limited and has to be used for transportation
Conclusion #2

The concept of demand-side-management has restricted potential.

A direct use of surplus electricity is advisable.

Transformation of surplus electricity into $\text{H}_2$ could be useful.

The production of secondary electricity is doubtful.

- Storage is a thermal system with high losses.
- Its operation also depends on weather conditions.
Conclusion #4

In the future, the discussion on energy savings will complement, maybe replace the one on energy production.

I doubt that a complete decarbonisation with intermittent RES will be possible:
   from 180 TWh today to 1300 TWh
   from 82 GW today to more than 1000 GW installed power
   with more than ½ million wind-turbines
Conclusion #5 and summary

The consequences of the “Energiewende”

Production in 2016:
- 78 TWh by wind
- 37.6 TWh by PV
- 20.5 TWh by hydro
- 47 TWh via biomass

the highest electricity price in Europe together with Denmark
24 b€ feed-in subsidy for an electricity value of 3 b€
Electricity export at the level of PV production
2016: 97 h with negative spot-market prices
Chain of phase-shift transformers around Germany
Partial destruction of traditional suppliers – stock market value, lay-offs
No creation of new technologies – PV producers went into insolvency
Polarisation of the general public because of high windmill density
No rewarding effect on Germany’s GHG emissions
Selection of supply technology

- **Peak power**
- **Storage filling**
- **Discharging** $\eta \approx 0.8$
- **Baseline supply**
- **Medium power range**

Merrit-order-curve

- **Minimum**
- **Average**
- **Peak**

http://et-energie-online.de/Portals/0/PDF/zukunftsfragen_2013_01_kranner.pdf
Power levels to be installed

Wind+PV power ~ peak load
Wind+PV ~ fossil + nuclear

Large overcapacity

Economic consequences

http://et-energie-online.de/Portals/0/PDF/zukunftsfragen_2013_01_kranner.pdf
Conclusion #1

Wind- and PV-power suffer from
  low power density
  intermittency

Consequences:
  large power capacities necessary
  surplus production
  back-up needed → 2 separate systems of largely different technology

  the back-up system requires a new economic model
    → capacity market