Fundamental Research on Renewable Energy Systems at the interface between engineering + mathematics + physics

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(1) 100% Renewable Energy Systems

(2) Complex Networks

(3) Wind-farm Modeling + Optimization

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Design of a highly renewable pan-European energy system

„Mehr als die Vergangenheit interessiert mich die Zukunft, denn in ihr gedenke ich zu leben.“

(Albert Einstein)
Design of a highly renewable pan-European energy system

More + more + ... renewables: what is the end of the story?
Anticipate the future!
Think backwards: 2050 → 2020!

Let the weather decide!
Let the weather decide!

\[ G_n^W(t) + G_n^S(t) + B_n(t) + \sum_{\text{ngb}(n)} F_{\rightarrow n} + S_n^- = L_n(t) + C_n(t) + \sum_{\text{ngb}(n)} F_{n\rightarrow} + S_n^+ \]

\[ \langle G_n^W + G_n^S \rangle = \gamma_n \langle L_n \rangle \]

\[ \langle G_n^W \rangle = \alpha_n \gamma_n \langle L_n \rangle \]

\[ \langle G_n^S \rangle = (1 - \alpha_n) \gamma_n \langle L_n \rangle \]

\[ G_n^W(t) + G_n^S(t) - L_n(t) = C_n(t) - B_n(t) + \sum_{\text{ngb}(n)} \left( F_{n\rightarrow} - F_{\rightarrow n} \right) + \left( S_n^+ - S_n^- \right) \]
Let the weather decide!

\[ G_{n}^{\text{RES}}(t) = G_{n}^{W}(t) + G_{n}^{S}(t) \]

Renewable Energy Atlas
2000 – 2007: 1h, 45x45km²
1980 – 2014: 1h, 30x30km²

\[ \langle G_{n}^{W} + G_{n}^{S} \rangle = \gamma_{n} \langle L_{n} \rangle \]

\[ \langle G_{n}^{W} \rangle = \alpha_{n} \gamma_{n} \langle L_{n} \rangle \]
\[ \langle G_{n}^{S} \rangle = (1 - \alpha_{n}) \gamma_{n} \langle L_{n} \rangle \]

\[ G_{n}^{W}(t) + G_{n}^{S}(t) - L_{n}(t) = C_{n}(t) - B_{n}(t) + \sum_{\text{ngb}(n)} \left( F_{n} - F_{n} \right) + \left( S_{n}^{+} - S_{n}^{-} \right) \]

actio = reactio
Technical + economical design of a highly renewable pan-European energy system

How much ...
... wind energy?
... solar PV energy?
... backup energy + power?
... transmission?
... storage?

and what about ...
... transition 2050 → 2020?
... future markets
... coupling of energy sectors?
How much backup?
How much wind + solar power?
Mismatch distribution (Germany)

\[ \Delta_n(t) = G_n^{RES}(t) - L_n(t) = C_n(t) - B_n(t) \]

\[ \langle G_n^{RES} \rangle = \langle L_n \rangle \]

\[ C_n(t) = \max(\Delta(t), 0) \]

\[ B_n(t) = -\min(\Delta(t), 0) \]
\[ \alpha_n = \frac{\langle G^W_n \rangle}{\langle G^\text{RES}_n \rangle} \]
Germany (DE)

$P(\Delta, \alpha = 0.1)$

Mismatch power [normalised]
Germany (DE)

$P(\Delta | L), \alpha = 0.5$
Mismatch distribution (Germany)

$$\Delta_n(t) = G_n^{RES}(t) - L_n(t)$$

$$\left\langle G_n^{RES} \right\rangle = \left\langle L_n \right\rangle$$

$$\alpha_n = \frac{\left\langle G_n^W \right\rangle}{\left\langle G_n^{RES} \right\rangle}$$

$$B_n(t) = -\min(\Delta(t), 0)$$

$$C_n(t) = \max(\Delta(t), 0)$$
BACKUP ENERGIES of EU countries (zero transmission)

\( \alpha_{\text{min}} \approx 0.70 \)

\( \langle B_n \rangle \approx 0.24 \)
Mismatch distribution (Europe)

\[ G_n^{RES}(t) - L_n(t) = C_n(t) - B_n(t) + \sum_{n \text{ngb}(n)} (F_{n\rightarrow} - F_{\rightarrow n}) \]

\[ \Delta_{EU}(t) = \sum_n G_n^{RES}(t) - \sum_n L_n(t) = G_{EU}^{RES}(t) - L_{EU}(t) \]

\[ = \sum_n (C_n(t) - B_n(t)) + \sum_n \sum_{n \text{ngb}(n)} (F_{n\rightarrow} - F_{\rightarrow n}) = C_{EU}(t) - B_{EU}(t) \]
Mismatch distribution: Germany vs. Europe

Mismatch without / with Transmission

Europe (EU)
- Load
- Aggregated Europe
- Individual countries

Mismatch power [normalised]
BACKUP ENERGIES of EU countries (with/without transmission)

- Wind fraction ($\alpha_n$): $0.70$
- EU wind fraction ($\alpha_{EU}$): $0.80$
- Annual balancing energy expectation ($\langle B_n \rangle$): $0.24$
- EU annual balancing energy expectation ($\langle B_{EU} \rangle$): $0.15$
Mismatch distribution: Germany vs. Europe

Mismatch without / with Transmission
BACKUP CAPACITY of EU countries (without/with transmission)
wind and solar power capacities

annual consumption (2009)
= 3360 TWh

70% wind power generation
= 875 GW installed capacity
= 175,000 x 5 MW turbines
= 4350 x 200 MW wind farms
≈ 115000 km²

30% solar PV power generation
= 550 GW installed capacity
≈ 3500 - 7500 km²
How much transmission?
transmission calculation without transmission

$\gamma = 1 \quad \alpha \approx 0.7$

minimum backup energy at optimal wind / solar mix

$B_{EU} = 0.15 \quad \text{vs.} \quad \sum_n B_n = 0.24$
transmission calculation without transmission

The **MAXIMUM BENEFIT OF TRANSMISSION** quantifies how much balancing/surplus can be reduced by sharing local surplus wind and solar power in an unconstrained pan-European transmission network.
How much transmission?

\[ \gamma = 1, \quad \alpha \approx 0.7 \]

\[
\min \sum_n B_n \quad \min \sum_l F_l^2
\]
Who pays for the transmission capacity?

\[
\left( \sum_l T_l^{2050} \right) \frac{\langle L_n \rangle}{\sum_m \langle L_m \rangle}
\]

\[
\sum_{l(n)} \frac{T_l^{2050}}{2}
\]

\[
\sum_l T_l^{2050} \rightarrow \text{export}(n)
\]
Who pays for the transmission capacity?

- **Export flow tracing**
  - Synchronised export usage $C_n / C^{90\%}$

- **Import flow tracing**
  - Synchronised import usage $C_n / C^{90\%}$

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Who pays for the transmission capacity?

\[
\left( \sum_l T_l^{2050} \right) \frac{\langle L_n \rangle}{\sum_m \langle L_m \rangle}
\]

\[
\sum_{l(n)} \frac{T_l^{2050}}{2}
\]

\[
\sum_l T_l^{2050} \leftarrow \text{export}(n)
\]
Who pays for the transmission capacity?

\[ \sum_l T_{l \leftarrow \text{export}(n)} \]

\[ \sum_l T_{l \leftarrow \text{import}(n)} \]
Levelized Cost of SYSTEM Energy
Levelized Cost of SYSTEM Energy

\[ \langle G_n^{RES} \rangle = \langle L_n \rangle \]
beyond EU: world-wide grid
beyond EU: world-wide grid
so far: backup + transmission

now: what about storage?
How much storage?  @ 100% penetration in EU

\[ G_n^W(t) + G_n^S(t) - L_n(t) = \sum_{ngb(n)} \left( F_{n-} - F_{n+} \right) + \left( S_n^+ - S_n^- \right) \]

\[ \Delta_{EU}(t) = G_{EU}^{RES}(t) - L_{EU}(t) \]

\[ S(t) - S(t-1) = \begin{cases} 
\eta_{in} \Delta(t) & (\Delta > 0) \\
\eta_{out}^{-1} \Delta(t) & (\Delta < 0) \end{cases} \]
How much storage? @ 100% penetration in EU

Seasonal optimal mix
= 60% wind power
+ 40% solar power
How much storage? @ 100% penetration in EU

\[ C_S = 10\% \langle L \rangle_{\text{annual}} \]

\[ = 340 \text{ TWh} \]

NOT POSSIBLE:
Pumped Hydro, Compressed Air

POSSIBLE:
H₂ storage
25 TWh = 0.008 av.y.l.
6h “battery” storage
2.2 TWh = 0.0007 av.y.l
Temporal correlations on the synoptic time scale cause the extremely enhanced need for storage energy capacity.

Beyond a penetration of $\gamma > 60\%$ a 6h storage (load flexibility, smart grid, v2g) is no longer sufficient!
What about synergies: balancing + storage?

“hydro/bio” balancing (150 TWh)
+ 6h “battery” storage (2.2 TWh, $\eta=1.0$)
+ seasonal H2 storage (25 TWh, $\eta=0.6$)
6h “battery” storage (2.2 TWh, $\eta=1.0$)  
+ seasonal H2 storage  
(25 TWh, $\eta=0.6$)  
+ “hydro/bio” balancing (150 TWh)

$\gamma = 1, \alpha = 0.8$:

$\langle B(t) \rangle_{EU} = 15\% \langle L \rangle_{\text{annual}}$

$= 510 \text{ TWh}$. 

Martin Greiner, 2012
6h "battery" storage + seasonal H2 storage + "hydro/bio" balancing

(2.2 TWh, η=1.0)
(25 TWh, η=0.6)
(150 TWh)
6h “battery” storage + seasonal H2 storage + “hydro/bio” balancing (2.2 TWh, η=1.0) (25 TWh, η=0.6) (150 TWh)
2015 ↔ 2050
Transition 0% $\rightarrow$ 100% renewables
Case: Denmark (without storage)

$$G_n^{RES}(t) - L_n(t) = C_n(t) - B_n(t)$$
Excess generation:

\[ \langle C_n(t) \rangle_t \]

[Diagram showing excess generation with various energy sources and their contributions.]

\[ G_n^W(t) + G_n^S(t) - L_n(t) = C_n(t) - B_n(t) + \left( S_n^+ - S_n^- \right) \]
Pan-European Transmission 2014 → 2050

(a) Germany (wind)
- Historical values
- Target values (base)
- Logistic fit (base)
- Logistic fit (+1%)
- Logistic fit (+2%)
- Logistic fit (+5%)

(b) Transmission layouts
- 70% benefit of transmission line capacities
- 90% benefit of transmission line capacities
- Unconstrained line capacities

(c) New line capacities per 5-year interval (normalised)
Pan-European Transmission 2014 → 2050
Denmark 2014 → 2050: Import / Export opportunities

- Import opportunities for Denmark:
  - Deficit
  - Import with unconstrained transmission
  - Import with 90% benefit of coop. transmission
  - Import with 70% benefit of coop. transmission
  - Import with transmission lines as of today

- Export opportunities for Denmark:
  - Excess generation
  - Export with unconstrained transmission
  - Export with 90% benefit of coop. transmission
  - Export with 70% benefit of coop. transmission
  - Export with transmission lines as of today

Reference year:
- 2015, 2020, 2025, 2030, 2035, 2040, 2045, 2050

Deficit (normalised)

Production (normalised)
Germany 2014 → 2050: Import / Export opportunities

Import opportunities for Germany:
- Deficit
- Import with unconstrained transmission
- Import with 90% benefit of coop. transmission
- Import with 70% benefit of coop. transmission
- Import with transmission lines as of today

Export opportunities for Germany:
- Excess generation
- Export with unconstrained transmission
- Export with 90% benefit of coop. transmission
- Export with 70% benefit of coop. transmission
- Export with transmission lines as of today
OUTLOOK
Fundamental Research on Renewable Energy Systems at the interface between engineering + mathematics + physics

SOME FUNDAMENTAL CHALLENGES:
storage phase transition, renormalisation scaling of power flows, spatio-temporal flow pattern pattern analysis, flow tracing, optimal heterogeneity, self-organizing power flows.
CONSENSYS

100% = 100+X% 

COMPLEX NETWORKS OF SMART ENERGY SYSTEMS
wind + solar + hydro + bio +
+ backup + transmission + storage,
electricity + heating + transportation

DESIGN OF FUTURE ENERGY MARKETS

OPTIMAL TRANSITION 2050 → 2020
Thank you!


D Heide et.al.: Reduced storage and balancing needs in a fully renewable European power system with excess wind and solar power generation, Renewable Energy 36 (2011) 2515-2523.


TV Jensen et.al.: Emergence of a phase transition for the required amount of storage in highly renewable electricity systems, EPJ ST on “Resilient power power grids and extreme events” (2014).


GB Andresen et.al.: The potential for arbitrage of wind and solar surplus power in Denmark, Energy (2014).


GB Andresen et.al.: Validation of Danish wind time series from a new global renewable energy atlas for energy system analysis, Energy (2014) submitted.