What can transmission do for a renewable Europe?

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Weather-driven electricity generation

Generation from weather data

Mismatch to load

\[ \Delta_n(t) = \gamma_n \left( \alpha_n^{W} W_n(t) + (1 - \alpha_n^{W}) S_n(t) \right) \langle L_n \rangle - L_n(t) \]

\( \Delta_n \) – mismatch at node \( n \), \( L_n \) – load, \( W_n \) – norm. wind generation, \( S_n \) – norm. solar PV generation, \( \gamma_n \) – gross VRES share, \( \alpha_n^{W} \) – relative wind share
Logistic fit

Logistic growth function: \[ f(y; y_0, a, b, m) = \frac{a \cdot b \cdot e^{m(y-y_0)}}{a(e^{m(y-y_0)}-1)+b} \]
End-point mixes

![Graph showing the relationship between End-point mixes and backup energy (normalised)].

- **Mix $\alpha_W$**: Represents the mix ratio of different energy sources.
- **Backup energy (normalised)**: Indicates the normalized backup energy for different mixes.
- **+1 % bal., PV**: Represents a backup energy increase of 1% for PV.
- **+2 % bal., PV**: Represents a backup energy increase of 2% for PV.
- **+5 % bal., PV**: Represents a backup energy increase of 5% for PV.
- **+1 % bal., wind**: Represents a backup energy increase of 1% for wind.
- **+2 % bal., wind**: Represents a backup energy increase of 2% for wind.
- **+5 % bal., wind**: Represents a backup energy increase of 5% for wind.

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DC power flow

Given $\Delta_n$ for all nodes $n$, solve for $F$:

\[
\begin{align*}
\Delta_n - (KF)_n &= 0 \quad \text{– cover deficits with surpluses} \\
\min \sum_l F_l^2 &= \text{– minimize transmission dissipation}
\end{align*}
\]

$\Delta_n$ – power surplus/deficit at node $n$,
$F_l$ – power flow along link $l$,
$K$ – incidence matrix, encodes network topology,
$(KF)_n$ – net flow out of node $n$
Generalisation

DC power flow only works for

- $\sum_n \Delta_n = 0$ – energy conservation
- Unconstrained flows

$\Rightarrow$ Generalisation:

$$\begin{align*}
\min \sum_n (\Delta_n - (KF)_n) - &= \min \sum_n B_n \quad \text{– minimize residual deficit} \\
\min \sum_l F_l^2 &= \min \quad \text{– minimize dissipation}
\end{align*}$$

- Back-up power to cover deficits if needed
- Shed surplusses if necessary
- Constraints on the transmission line capacities
  $$h_l - F_l \leq F_l \leq h_l$$
Two extreme cases:

- No transmission – $C_{\text{zero}}$
  $\Rightarrow$ high total back-up energy $B_{\text{tot}}(C_{\text{zero}})$

- Unconstrained transmission – $C_{\text{unconstrained}}$
  $\Rightarrow$ low total back-up energy $B_{\text{tot}}(C_{\text{unconstrained}})$

**Benefit of transmission of a general transmission layout $C_{CL}$:**

$$\beta_{CL} = \frac{B_{\text{tot}}(C_{\text{zero}}) - B_{\text{tot}}(C_{CL})}{B_{\text{tot}}(C_{\text{zero}}) - B_{\text{tot}}(C_{\text{unconstrained}})}$$

Resonable compromise:

90% benefit of transmission capacities
Which links should be reinforced first?

- Multiples of today’s capacities
- Different quantiles of unconstrained flow
Quantile line capacities

Flow histogram PL to DE
- Unconstrained flow
- 99% Quantile
- Installed today
- 99.9% Quantile
- 100% Quantile

Occurences (normalized)

Nonzero, directed power flow/GW

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Network evolution

2010

Gross share of wind and solar power

Power transfer capacity

≤ 0.7 GW
≤ 1.5 GW
≤ 2.5 GW
≤ 4.0 GW
≤ 6.0 GW
≤ 10.0 GW
≤ 15.0 GW
≤ 20.0 GW
≤ 25.0 GW
> 25.0 GW

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2030

Gross share of wind and solar power

Power transfer capacity

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2040

Gross share of wind and solar power

Power transfer capacity

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2050

Gross share of wind and solar power

Power transfer capacity

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Investment per five year interval

Logistic growth of wind (a) and solar PV (b) power

Growth in 90% benefit line capacities (a) and incremental investment per five-years (b)
Denmark

Import opportunities for Denmark
- Deficit
- Import with $CL_{unconstrained}$
- Import with $CL_{90\%}$
- Import with $CL_{today}$

Export opportunities for Denmark
- Excess generation
- Export with $CL_{unconstrained}$
- Export with $CL_{90\%}$
- Export with $CL_{today}$
Spain

Production (normalised)

Import opportunities for Spain
- Deficit
- Import with CL unconstrained
- Import with CL 90%
- Import with CL today

Export opportunities for Spain
- Excess generation
- Export with CL unconstrained
- Export with CL 90%
- Export with CL today

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France

Import opportunities for France
- Deficit
- Import with $CL_{unconstrained}$
- Import with $CL_{90\%}$
- Import with $CL_{today}$

Export opportunities for France
- Excess generation
- Export with $CL_{unconstrained}$
- Export with $CL_{90\%}$
- Export with $CL_{today}$
Germany

Import opportunities for Germany
- Deficit
- Import with CL unconstrained
- Import with CL 90%
- Import with CL today

Export opportunities for Germany
- Excess generation
- Export with CL unconstrained
- Export with CL 90%
- Export with CL today

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Denmark

Mismatch between load and generation (normalised)

Denmark, reference year 2030
\[\gamma_{DK} = 0.78, \quad \gamma_{avg} = 0.55\]

- Load
- Mismatch before sharing renewables
- Mismatch after sharing, Line capacities as of today
- Mismatch after sharing, 90% benefit of transm. line capacities

Denmark, reference year 2050
\[\gamma_{DK} = 0.98, \quad \gamma_{avg} = 0.98\]

- Load
- Mismatch before sharing renewables
- Mismatch after sharing, Line capacities as of today
- Mismatch after sharing, 90% benefit of transm. line capacities
Spain

Mismatch between load and generation (normalised)

Spain, reference year 2030
$\gamma_{\text{ES}} = 0.70$, $\gamma_{\text{avg}} = 0.55$

Mismatch before sharing renewables
Mismatch after sharing, Line capacities as of today
Mismatch after sharing, 90% benefit of transm. line capacities

Spain, reference year 2050
$\gamma_{\text{ES}} = 0.97$, $\gamma_{\text{avg}} = 0.98$

Mismatch before sharing renewables
Mismatch after sharing, Line capacities as of today
Mismatch after sharing, 90% benefit of transm. line capacities
France

Mismatch between load and generation (normalised)

France, reference year 2030
$\gamma_{FR}=0.50$, $\gamma_{avg}=0.55$

- Load
- Mismatch before sharing renewables
- Mismatch after sharing, Line capacities as of today
- Mismatch after sharing, 90% benefit of transm. line capacities

France, reference year 2050
$\gamma_{FR}=0.99$, $\gamma_{avg}=0.98$

- Load
- Mismatch before sharing renewables
- Mismatch after sharing, Line capacities as of today
- Mismatch after sharing, 90% benefit of transm. line capacities
Germany

Mismatch between load and generation (normalised)

- Germany, reference year 2030:
  - Load: \( \gamma_{DE} = 0.63, \gamma_{avg} = 0.55 \)
  - Mismatch before sharing renewables
  - Mismatch after sharing, line capacities as of today
  - Mismatch after sharing, 90% benefit of transmission line capacities

- Germany, reference year 2050:
  - Load: \( \gamma_{DE} = 0.97, \gamma_{avg} = 0.98 \)
  - Mismatch before sharing renewables
  - Mismatch after sharing, line capacities as of today
  - Mismatch after sharing, 90% benefit of transmission line capacities

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End-point mixes

\[ \alpha_{opt, \text{EU agg.}} = 0.894, \quad \alpha_{opt, \text{EU avg.}} = 0.794 \]
Wind resources decorrelate at distances around 500–1000 km
Linecaps/Backup tradeoff

Scenarios
- +5% backup, PV
- +2% backup, PV
- +1% backup, PV
- Backup optimal
- +1% backup, wind
- +2% backup, wind
- +5% backup, wind

Total line capacities (normalised)

Backup energy (normalised)
Conclusions

Model ingredients:

- Weather-based modelling
- Logistic growth of renewable installations
- DC power flow

Results:

- Quantile line capacities useful approach
- Quadrupling today’s line capacities yields 90% of potential benefit
- Transmission reduces backup energy by up to 40% BUT does not provide last-resort secure capacity
- Especially during critical times, backup power is not much reduced